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NASA-CR-162071

TESTING AND FAILURE ANALYSIS TO IMPROVE SCREENING TECHNIQUES FOR HERMETICALLY SEALED METALLIZED FILM CAPACITORS FOR LOW ENERGY APPLICATIONS

FINAL REPORT

CONTRACT NUMBER NAS 8-33957

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FOREWORD

This report documents the work performed by the Electronics Division, Union Carbide Corporation, during the period 12 August 1980 to 30 June 1982 for NASA, Marshall Space Flight Center, under Contract NAS 8-33957. NASA Program Manager was E. L. Bombara; Union Carbide Corporation Program Manager was W. C. Lamphier.

SUMMARY

Some terms used in this report are peculiar to metallized dielectric capacitors. The following definitions will apply to these terms:

Fault:

A defect site in a metallized capacitor which causes shorting or low insulation resistance to occur during capacitor operation.

Clearing:

The process that occurs when the stored energy in the capacitor is discharged through the fault, vaporizes the metallized electrode, and restores the capacitor to an operative condition.

Momentary Breakdown:

A period of indeterminate duration, usually less than 0.5 second, during which the capacitor goes into a short circuit mode and is cleared. This condition always generates a noise pulse in the circuit where the capacitor is used.

Self Healing:

A property of metallized capacitors which obviates short circuit failures by clearing dielectric faults.

The objective of this program was to evaluate and recommend effective screening techniques, through testing and failure analysis, for detecting insulation resistance degradation and failure in hermetically sealed metallized film capacitors used in applications where low capacitor voltage and energy

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levels are common to the circuitry. In these applications, the stored energy is usually believed to be insufficient to clear shorts and low resistance faults in metallized dielectric capacitors.

A candidate screening technique, in which the capacitors were monitored for pulses while subjected to varying voltage levels at 100°C, was evaluated and compared with the screening procedure outlined in Table III of MIL-C-83421. A special test and monitoring system capable of rapidly scanning all test capacitors and recording faults and/or failures was developed. This system was used to monitor the capacitor current during the special screening procedure and at regular readout intervals during the environmental exposure testing.

Test groups represented different raw material lots, film thicknesses, winding constructions and film types. The capacitors were subjected to the following environmental exposure testing to evaluate the efficacy of screening techniques and to assess device reliability:

Temperature Cycle	(-65°C to +100°C; 300 cycles)
High Temperature Storage	(+125°C; not energized; 2000 hours)
Low Voltage Life Test	(2.5 VDC; 25°C; 2000 hours)
Medium Voltage Life Test	(5.7 VDC: 25°C; 2000 hours)
High Voltage Life Test	(30 VDC; 25°C; 2000 hours)

Post screening tests of the electrical parameters of capacitance, dissipation factor and insulation resistance on special and standard screened capacitors revealed only minor differences in capacitance stability with the special screened groups being more stable. All other parameters were nearly identical for the test groups

A permanent record was maintained of all units which faulted and/or failed post test insulation resistance. Of the 1200 units tested, 236 such

devices were found; of these, 118 failed post test insulation resistance, while 118 faulted and cleared, only. The data and failed devices were analyzed with the following results:

1- Capacitors subjected to the special screening technique of this study exhibit higher reliability than those screened by standard MIL screening techniques.

2- Exposure to temperatures above 100°C affects the reliability of polycarbonate capacitors more than it does polysulfone film units.

3- Device reliability was related to raw material lot.

4- Raw material lots exhibit differences in characteristics which may be related to finished capacitor reliability.

5- Polysulfone film capacitors exhibited higher reliability than polycarbonate film units at elevated temperatures.

6- Life tests at 25°C generated the least number of failures and show no significant reliability difference between polycarbonate and polysulfone film capacitors.

7- Multiple sheet insulating systems normally exhibit advantages over single sheet systems, except after prolonged high temperature exposure.

8- The vast majority of failures, after screening, were short circuit and/or low insulation resistance.

9- On the average, metallized film capacitors in this study will clear with approximately 20 μJ stored energy.

10- Clearing does not necessarily indicate that the devices exhibiting the condition will subsequently fail.

INTRODUCTION

The volumetric efficiency and self-healing characteristics of metallized film capacitors have made them highly desirable for use in applications where size and weight are critical, short circuit failures must be avoided and occasional momentary breakdowns and/or periods of low insulation resistance can be tolerated. For these reasons, these devices have been enjoying wider applications in space and aircraft electronic applications.

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Sporadic failures of metallized film capacitors in recent space missions have caused concern regarding the reliability of these devices, particularly in low voltage, high impedance circuits where levels of stored capacitor energy are below those believed necessary to clear dielectric faults. The phenomenon of low voltage failures in metallized capacitors has been reported previously. In 1967, in work performed by TRW,[1/] metallized polycarbonate capacitors were found to be shorted at voltages below 10 VDC. The reasons for these failures have been the subject of conjecture, but were generally believed to be the result of metal migration back into the fault sites.

The recent failure of a metallized polycarbonate capacitor on a Voyager mission refocused attention on this failure mode and the reliability of metallized film capacitors, particularly in low voltage, high impedance circuits. Of particular interest is the efficacy of screening procedures and techniques which could identify devices which are prone to failure. Investigations at JPL,[2/] while essentially duplicating the failure mode, did not positively identify the causative factors, but indicated material lot variability as a probability and suggested screening capacitors by a technique which would identify capacitors which exhibit clearing and eliminate those from the population as they would be the most likely to fail.

This evaluation program was initiated to determine if the potential causes of metallized film capacitor failure at low voltage can be identified and if screening techniques capable of identifying failure prone capacitors can be developed.

The contract specified which tests were to be performed, outlined conditions for the special screening test, established readout periods and post test electrical parameters and defined test group size and content. The scope

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of work was to fabricate capacitors and test them, as specified, and evaluate the data to determine the efficacy of the screening test and make recommendations based on the data.

The objective of this program was to evaluate and recommend screening techniques, through testing and failure analysis, for metallized capacitors in low voltage, high impedance circuits. The test program was designed to determine which effects, or combination of effects — thermal, mechanical or electrical — are most probable causative factors in generating failures. The specific program tasks were

(1) Fabrication of test samples

(2) Screening of test samples by standard and special procedures

(3) Electrical characteristics of screened capacitors

(4) Environmental testing with monitored ramp voltage and temperature tests at specified intervals

(5) Analysis of data and failures

(6) Conclusions and recommendations

EXPERIMENTAL

A test matrix consisting of 12 groups, each with 20 capacitors, was designed to evaluate the various factors and screening techniques. The factors that were considered for evaluation for their probable impact on capacitor performance were

- Changes in raw material lot
- Changes in dielectric film type
- Differences in screening test procedure
- Two layer vs. one layer insulating systems using same thickness film
- Two layer thin sheet vs. one layer thick sheet insulating systems

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Each group was identified with a code indicating film, film lot, single or double layer, and whether standard or special screened. A description of the code is shown in Table I. To assure that the film lots used were truly different, both manufacturers agreed to supply film from two separate batches of base resin. In this manner, any differences would be related to raw material, rather than processing differences.

All test capacitors were fabricated using the same production line and process technique. While not all units were processed at the same time, the standard and special screened lots in each group were processed simultaneously. Actually, all single layer, 2 μm polycarbonate groups were processed at the same time. The double layer, the 3.5 μm and the polysulfone groups were processed individually. After finishing, the capacitors were separated into the "X" and "Y" groups for screening. All of the standard screened devices were continued through the normal process; the units to be special screened were split from the group and prepared for further screening. The screening test conditions for both groups are detailed in Table II. It should be noted that, since the objective was to evaluate screening techniques at low voltages, the capacitors were not subjected to the routine electrical tests as these would apply high voltage to the parts. Consequently, the capacitors were subjected to the special screening test with no prior application of voltage other than the in-process fault clearing step when the capacitors are subjected to a voltage in excess of twice rated voltage. A flow chart showing the sequence of operations for the testing is presented in Figure 1.

TABLE I

TEST LOT IDENTIFICATION

TEST GROUP	IDENTIFICATION	MATERIAL LOT	NOMINAL RATING
SPCAX	SINGLE LAYER 2 μm PC	LOT A	4.6 μF/30V
SPCAY	SINGLE LAYER 2 μm PC	LOT A	4.6 μF/30V
SPCBX	SINGLE LAYER 2 μm PC	LOT B	4.6 μF/30V
SPCBY	SINGLE LAYER 2 μm PC	LOT B	4.6 μF/30V
SPCCX	SINGLE LAYER 2 μm PC	LOT C	4.6 μF/30V
SPCCY	SINGLE LAYER 2 μm PC	LOT C	4.6 μF/30V
DPCAX	DOUBLE LAYER 2 μm PC	LOT A	5.6 μF/30V
DPCAY	DOUBLE LAYER 2 μm PC	LOT A	5.6 μF/30V
DTPDX	SINGLE LAYER 3.5 μm PC	LOT D	5.6 μF/30V
DTPDY	SINGLE LAYER 3.5 μm PC	LOT D	5.6 μF/30V
SPSAX	SINGLE LAYER 2 μm PS	LOT A	4.6 μF/30V
SPSAY	SINGLE LAYER 2 μm PS	LOT A	4.6 μF/30V

NOTES: Groups coded "X" are standard screened. (Per MIL-C-83421)
Groups coded "Y" are special screened. (Per Contract)
PC - polycarbonate film; PS - polysulfone film.
Film Lots A and B from Manufacturer 1.
Film Lots C and D from Manufacturer 2.
Polysulfone film from Manufacturer 2.

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TABLE *

SCREENING TEST CONDITIONS

A - STANDARD SCREENING TEST PROCEDURES

Inspection	Requirement paragraph	Test method paragraph	AQL (percent defective)	
			Major	Minor
Subgroup 1				
Burn-in (when specified, see 3.1) - - - - - - -	3.6	4.7.2	Not applicable (100% inspection)	
Subgroup 2				
Thermal aging (when specified see 3.1) - -	3.7	4.7.3	Not applicable (100% inspection)	
Seal - - - - - - - - - - -	3.9	4.7.5		
Dielectric withstanding voltage - - -	3.10	4.7.6		
Insulation resistance- -	3.11	4.7.7		
Capacitance - - - - - -	3.12	4.7.8		
Dissipation factor - - -	3.13	4.7.9		
Dielectric absorption (when specified, see 3.1) - - - - - - - - -	3.14	4.7.10		

* Burn-in is 48 hours at 125°C with 1.4 V_R applied (V_R at 125°C = 0.5 V_R at 100°C).

B - SPECIAL SCREENING TEST PROCEDURES

1. Temperature cycle - 50 cycles, -55 to +125°C
2. Seal test - fine and gross leak
3. 2 cycles; 0-2.5-0 VDC at 100°C with scan
4. 24 hour burn-in at 1 VDC at 100°C; with scan
5. Insulation resistance at 25°C with 1 VDC applied
6. Capacitance and D.F. at 1 and 10 KHz
7. Raise voltage to 42 VDC at 100°C; burn-in for 120 hours; with scan
8. Lower voltage to 1.5 VDC at 100°C; burn-in for 48 hours; with scan
9. Raise voltage to 33 VDC; with scan
10. Reduce voltage to 30 VDC; measure insulation resistance at 100°C
11. Reduce voltage to 0 VDC; reduce temperature to 25°C
12. Insulation resistance at 25°C; 30 VDC
13. Capacitance and D.F. at 1 and 10 KHz
14. Repeat seal test (Step 2)
15. Inspect and serialize

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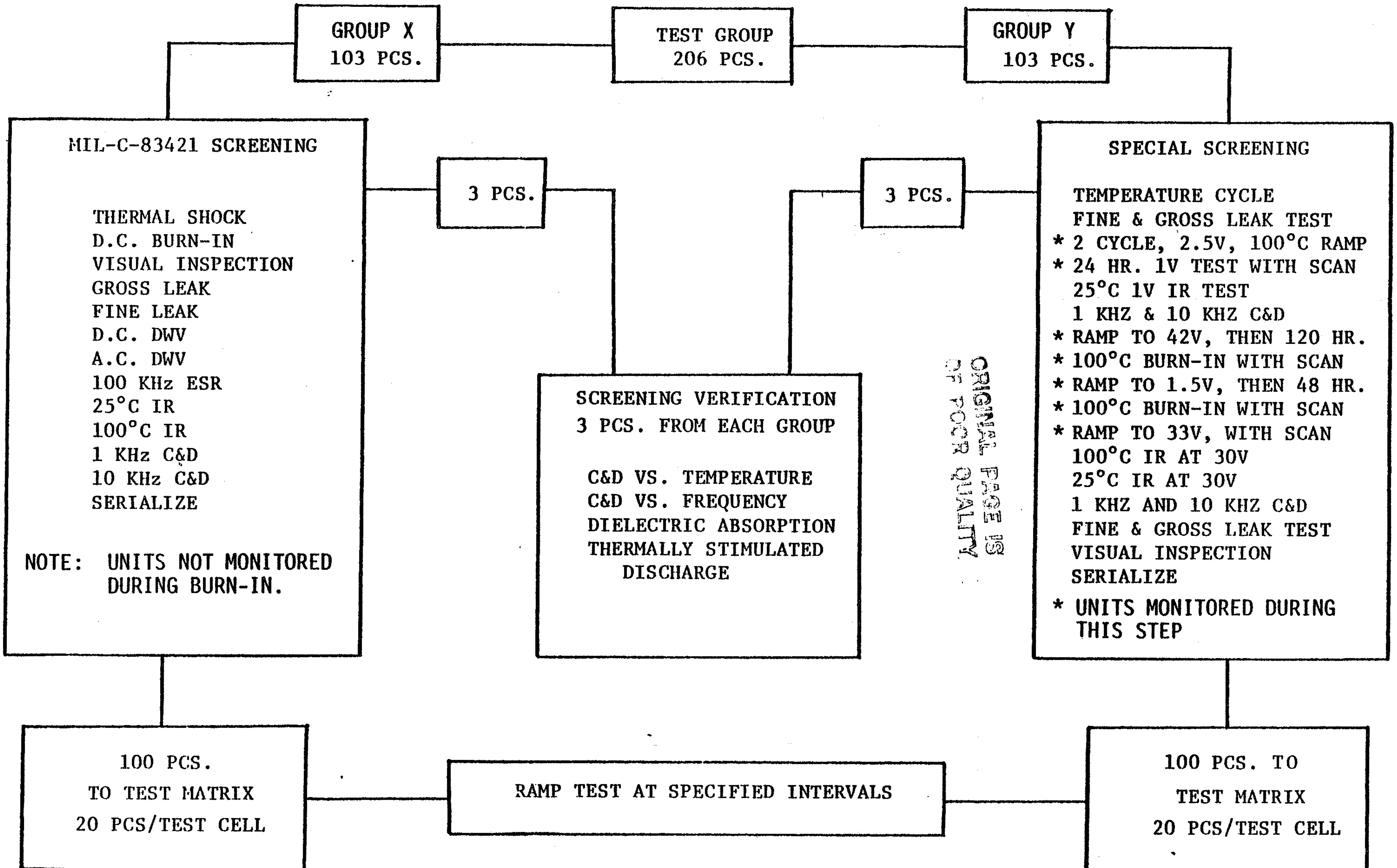

FIGURE 1: TEST PLAN FLOW CHART

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SPECIAL SCREENING

The special screening test was intended to identify those capacitors which were susceptible to clearing, since it was conjectured these would most likely fail. As low voltage, high impedance applications were being evaluated, each capacitor was tested with a 1.1 megohm resistance in series. The test circuit is shown in Figure 2. The detailed test procedure is listed in Table II, B. Phase I is represented in Steps 1 to 6, inclusive; Phase II is described in Steps 7 to 15, inclusive. The standard screening procedure is listed in Table II, A.

RAMP TEST AND MONITORING SYSTEM

The ramp test was patterned after the technique used by JPL during their initial investigations. The objective of the test was to determine whether capacitors faulted, at what voltage faulting occurred and the minimum level of stored energy required to effect clearing. During the test, the capacitors would be subjected to a voltage ramp while being temperature cycled. Figure 3 details the ramp test voltage and temperature profiles.

The ramp test was scheduled to be performed at specified readout intervals and, at the end of, the environmental exposure testing. The environmental tests and readout intervals are tabulated below.

TEST	READOUT INTERVAL
TEMPERATURE CYCLE	10; 50; 100; 200 and 300 CYCLES
HIGH TEMPERATURE STORAGE	100; 500; 1000 AND 2000 HOURS
LOW VOLTAGE LIFE (2.5 VDC)	100; 500; 1000 AND 2000 HOURS
MEDIUM VOLTAGE LIFE (5.7 VDC)	100; 500; 1000 AND 2000 HOURS
HIGH VOLTAGE LIFE (30 VDC)	100; 500; 1000 AND 2000 HOURS

FIGURE 2

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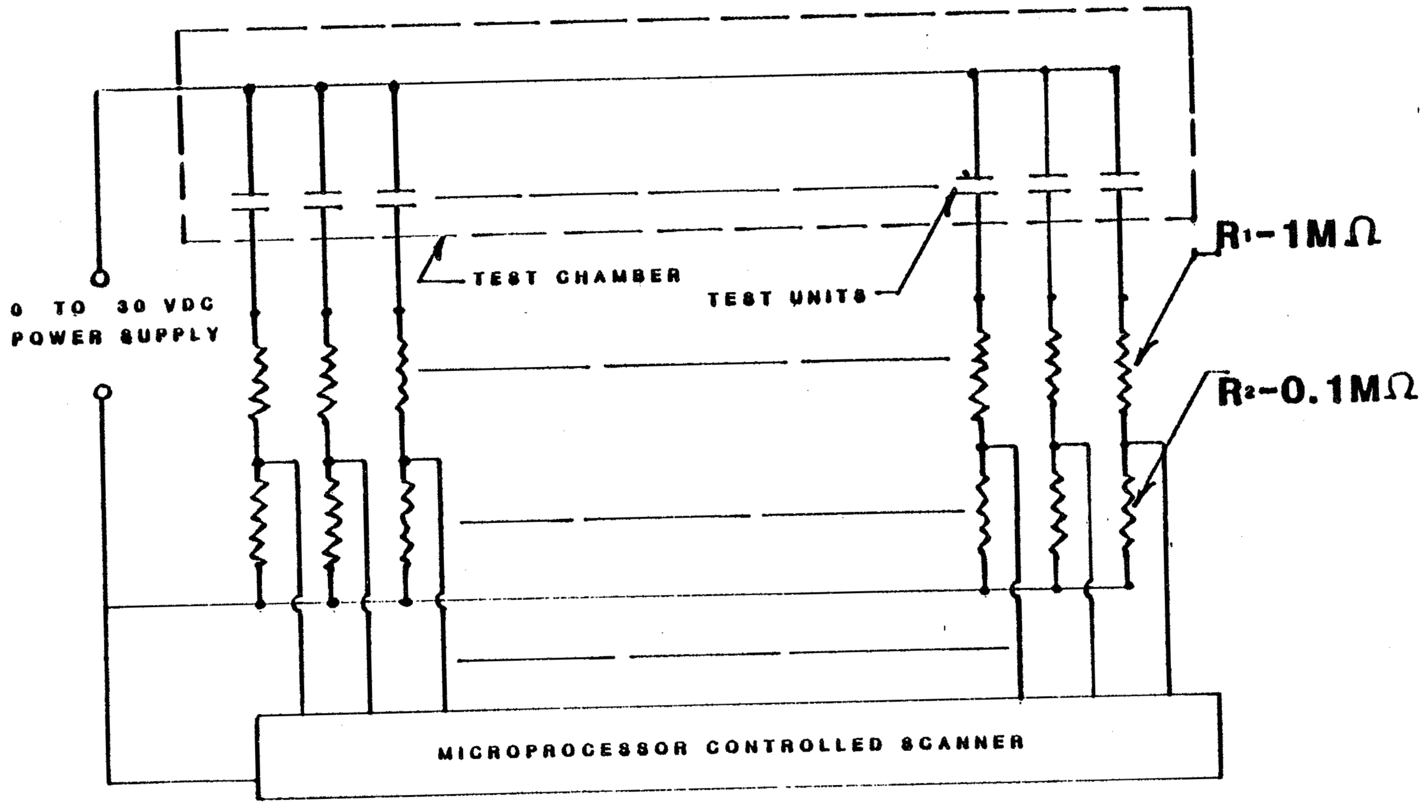
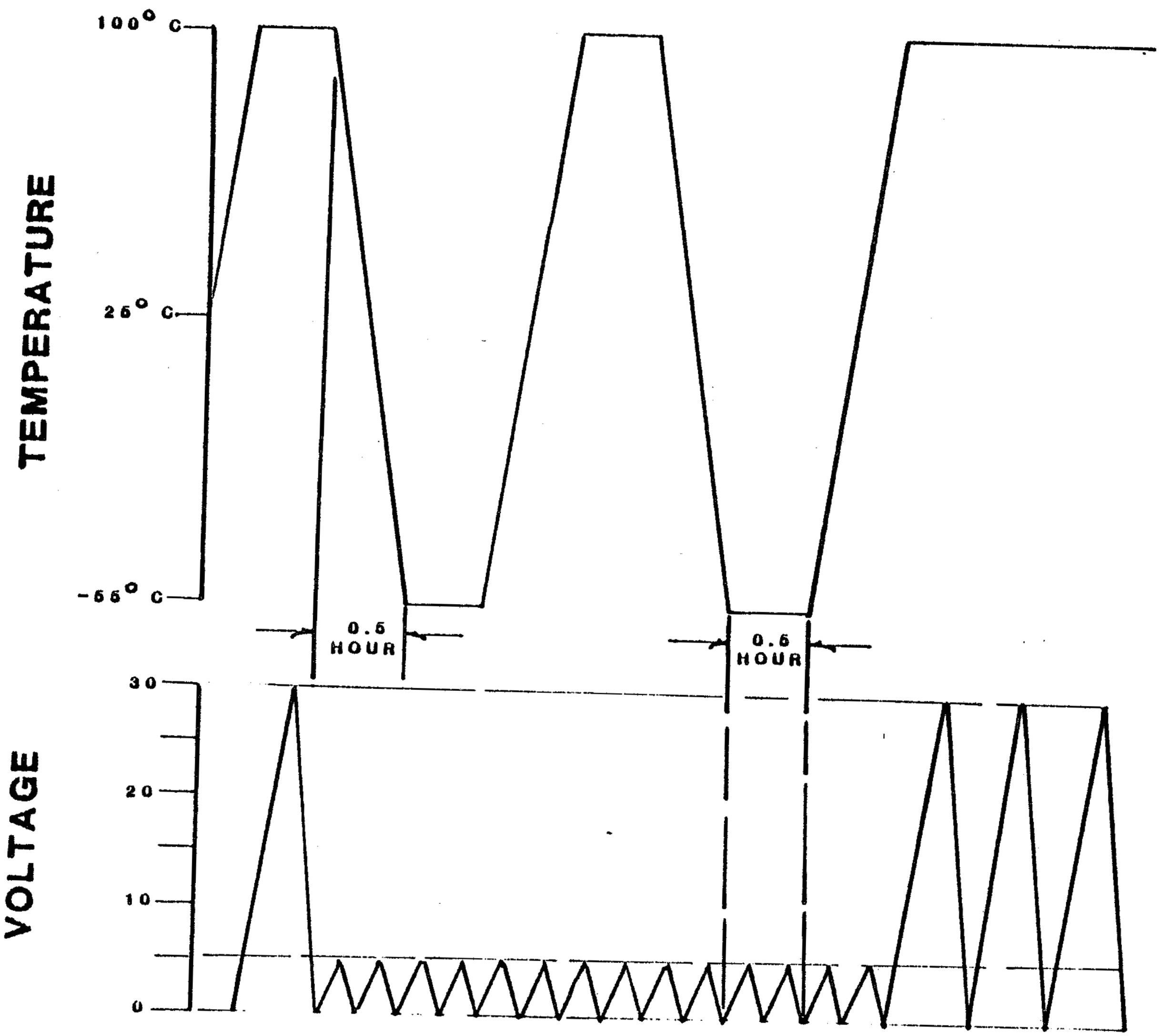


CAPACITOR TEST CIRCUIT

FIGURE 3



VOLTAGE AND TEMPERATURE PROFILES

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The monitoring system was required to continuously sense the current in each test capacitor, detect the voltage at which clearing or failure occurred, identify the device exhibiting the fault and provide data from which the energy used in clearing the fault could be calculated. The system, which is called the scanner, was used to monitor the test specimens during special screening tests, as well as during the readout interval ramp tests. To accomplish this task, a microprocessor-controlled scanner and detector system was designed. The objectives of this system were

- to be a stand alone, operator interfaced system
- to monitor each of the 240 test specimens at least twice each second
- to control the change and rate of change in the ambient temperature and applied voltage
- to record all fault events and data
- to calculate fault energy content for each event
- to calculate the statistical distribution of the data
- to accommodate test periods up to 168 hours in length
- to be unaffected by power failure
- to provide a hard copy of all data for review and analysis

The hardware portion of the system consisted of the following:

- hot and cold environmental chamber with special door for holding circuit cards with test specimens
- multiplexer type scanner
- programmable power supply
- digital thermometer
- control and data acquisition system consisting of
    - (a) M68MM19 monoboard 6809 microcomputer
    - (b) 32K EPROM board

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(c) 16K non-volatile static RAM

(d) cassette tape data recording outsystem

(e) combination I/O module

(f) analog to digital converter

(g) IEEE 488 interface controller board

(h) universal time generator board

(i) battery backup system

- cathode ray tube terminal
- printer

The cathode ray tube terminal is for operator communication with the system; the printer provides for a hard copy of all data. A block diagram of the system is shown in Figure 4.

Software for the system was written to allow the operator to input commands to configure the system as desired, within specified limits. Parameters such as system sensitivity, chamber temperature and rates of heating and cooling, applied voltage and rate of change in voltage, current level to indicate short circuit conditions and selection of which units are to be monitored are typical of those over which the operator has control. The CRT displays the status of the test, including voltage, temperature, time, number of scans and current status of the test units that are being monitored. An operating guide, system description and software package have been prepared for the system.

The system sensitivity is shown in Figure 5 and is based on a change in capacitor voltage, V_C. As presently set, if V_C changes by more than 0.0625 volts, the system records the voltage across R_2. This voltage is then used to calculate the change in the stored energy of the capacitor. This value also

FIGURE 4

BLOCK DIAGRAM OF TEST SYSTEM

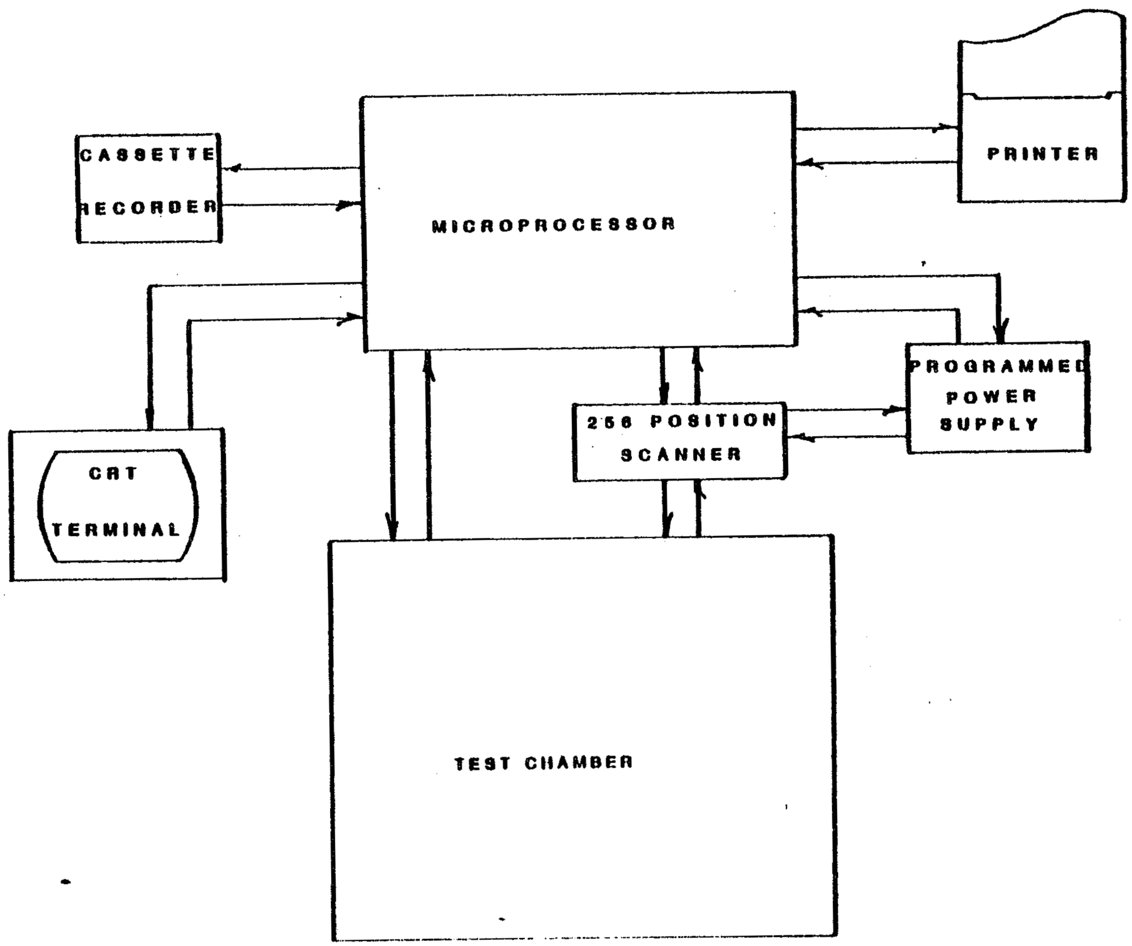

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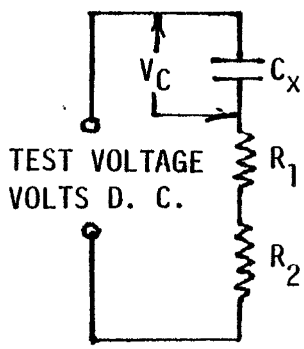
FIGURE 5

TEST CIRCUIT
FOR
INDIVIDUAL
CAPACITORS



NOTES:

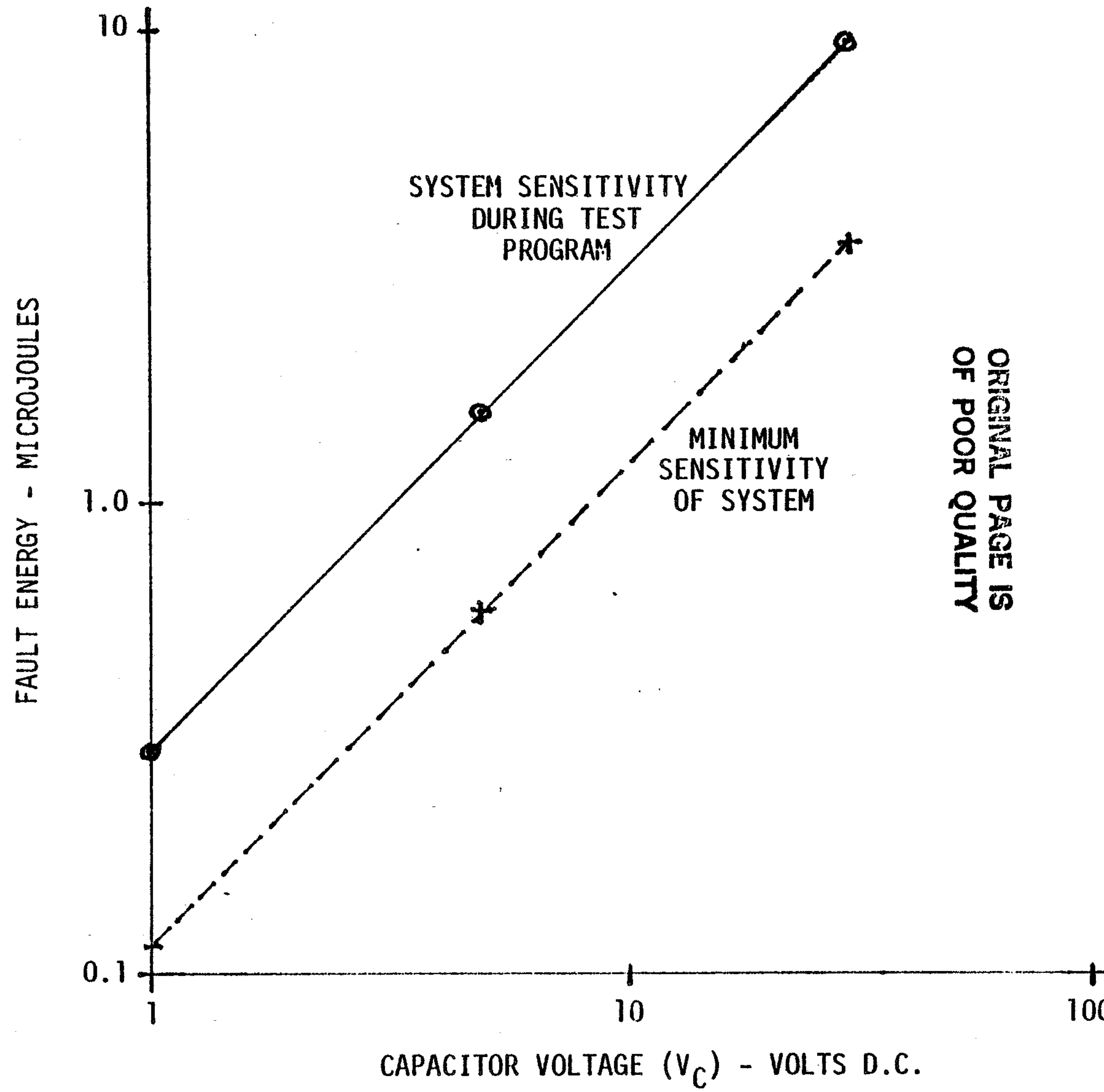
C_X = TEST CAPACITOR

R_1 = 1 MEGOHM

R_2 = 0.1 MEGOHM

V_C = CAPACITOR VOLTAGE IN VOLTS D. C.

SENSITIVITY OF FAULT DETECTION SYSTEM



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TEST CIRCUIT AND SYSTEM SENSITIVITY

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represents the energy used to clear the fault. The graph shows the minimum energy pulse which the system is capable of sensing (dashed line of Figure 5) and how it varies directly with the capacitor voltage.

For the actual testing, the system was set to respond to the level shown by the solid line of the graph and corresponded to energy levels of 0.3 μJ at 1 volt, 3.1 μJ at 5 volts and 10.3 μJ at 30 volts.

Formulae for calculating the energy expended in each fault and for calculating the means and standard deviation of the fault energy in each capacitor were also included in the software. Finally, programs to print out the data were included to make the system truly independent.

The formulae for calculating the energy required to clear a fault are reviewed below and describe the technique used in the system.

The energy stored in a capacitor is given by

(1) $$W = 1/2\ CV^2$$ where W = energy in joules
C = capacitance (farads)
V = voltage (volts)

When a fault occurs, the energy used by the fault causes the capacitor voltage, V, to drop to a new value, V^1.

The new value of the stored energy is given by

(2) $$W' = 1/2C\ V'^2$$

and the energy used by the fault is given by

(3) $$\Delta W = W - W'$$

or, can be calculated directly using the formula

4) $$\Delta W = 1/2C\ \left(V^2 - V'^2\right)$$

In the circuit of Figure 5, the voltage developed across R_2 and the capacitor test voltage are both recorded when a fault occurs. Since R_2 is ~1/11 of the total of R_1 and R_2, the voltage developed across R_1 plus R_2 is 11

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times that across R_2. It also represents the change in voltage on the capacitor due to the fault. Therefore, the energy used during the fault is calculated, using

$$\Delta W - 1/2C \left[V_C^2 - \left(V_C - 11V_R\right)^2\right] \tag{5}$$

where W = change in energy (joules)
C = capacitance (farads)
V_C= capacitor voltage (volts)
V_R= voltage across R_2 (volts)

As an example, assuming V_C to be 17.5 VDC and V_R to be 0.0265 VDC, the fault energy, calculated using equation (5) is

$$\Delta W = 1/2(5\times10^{-6}) \left[(17.5)^2 - (17.5-0.2915)^2\right]$$

$$= 2.53\times10^{-5} \text{ joules}$$

In this instance, the fault energy was 25.3 μJ.

For successive faults within the RC time constant of the test circuit with no change in test voltage, the software automatically reduces the value of the capacitor voltage to reflect both discharge and recharge prior to calculating the new value of energy. Photographs of the system are presented in Figures 6, 7, 8, and 9.

SPECIAL SCREENING TEST DATA

All "Y" coded test groups were subjected to the special screening test shown in Figure 1 and previously detailed. During the test, all capacitors were monitored, while voltage was applied, using the scanner. The screening test consisted of a low voltage phase (Phase I) and a high voltage phase (Phase II).

The performance of the test groups is summarized in Table III. Categories listed in the table are defined as follows:

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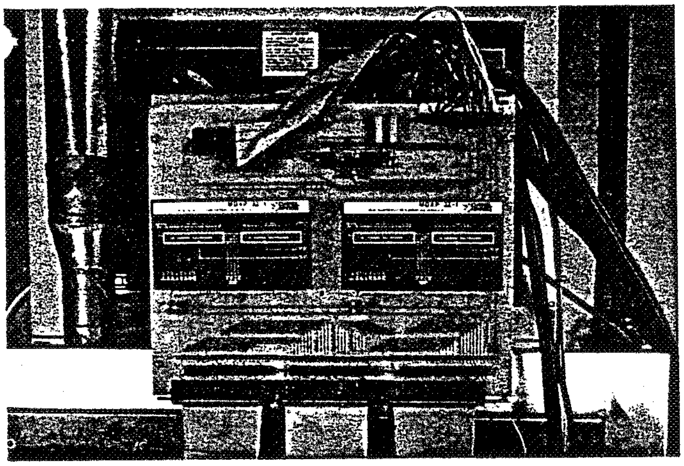

Figure 6. Detail showing multiplexer boards.

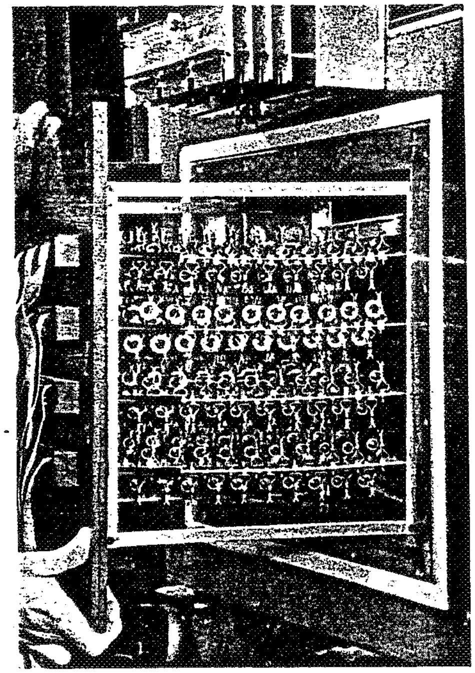

Figure 7. Test capacitors on cards; ready to test.

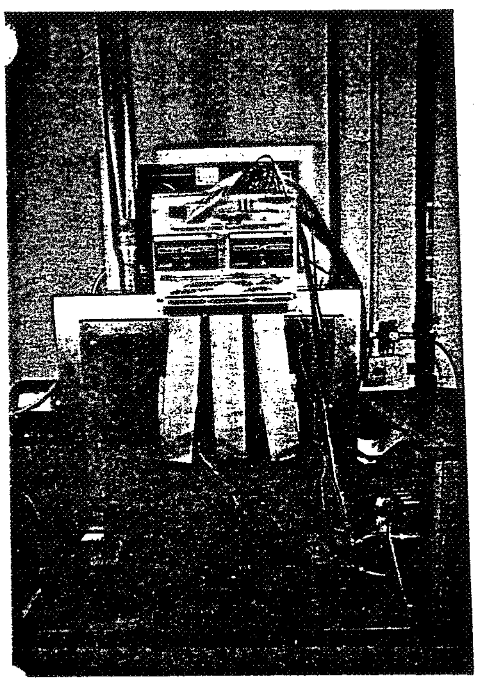

Figure 8. Test chamber loaded and ready to begin testing.

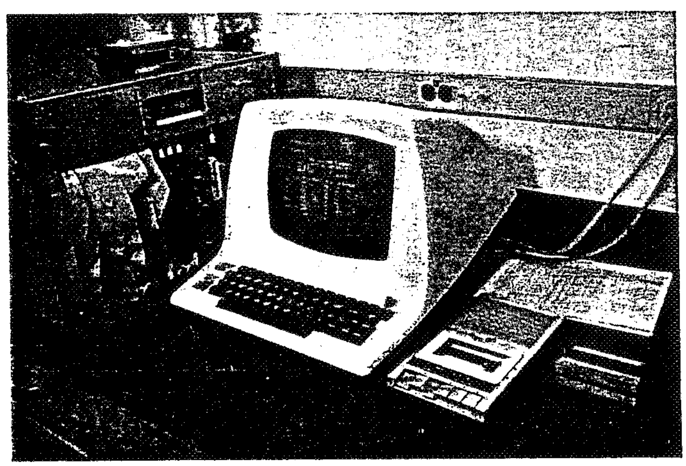

Figure 9. Detail showing microcomputer, cassette recorder and CRT terminal.

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TABLE III

SPECIAL SCREENING TEST DATA SUMMARY

PHASE I - 2.5 VDC MAXIMUM VOLTAGE

TEST GROUP	NO. OF STARTS	SHORTS	FAULTS	CLEAN UNITS
SPCAY	140	1	0	139
SPCBY	140	0	0	140
SPCCY	113	2	0	111
DPCAY	120	2	1	117
DTPDY	140	0	4	136
SPSAY	134	4	1	129

PHASE II - VOLTAGES TO 42 VDC APPLIED

TEST GROUP	NO. OF STARTS	SHORTS & I.R. FAILS	FAULTS	CLEAN UNITS	ACCEPTABLE CAPACITORS
SPCAY	140	25	17	98	115
SPCBY	140	22	19	99	118
SPCCY	113	3	14	96	110
DPCAY	120	3	7	110	117
DTPDY	140	20	18	102	120
SPSAY	134	27	26	81	107

NOTES: No. of starts includes a makeup run to assure 103 acceptable capacitors for all groups.

Quantity of shorts and I.R. fails and faults in Phase II includes units from Phase I in the same category.

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- Units classified as shorts failed to clear during the screening test, and insulation resistance was less than 10 megohms.

- Units classified as faults, or faulting, exhibited clearing during the screening tests. These may or may not have been acceptable for insulation resistance after screening.

- Units classified as clean did not exhibit faulting or clearing during the screening test and fully complied with MIL-C-83421, Group A, test requirements.

- Units classified as acceptable may or may not have faulted and cleared during the screening test, but did comply with MIL-C-83421, Group A, test requirements.

The data show the double layer test group (DPCAY) had the least number of combined faults and failures (10). The polysulfone group had the greatest (53). Of the single layer test groups, Lot C film (SPCCY) had the best reliability.

Including a makeup run to guarantee all lots would have 103 electrically good capacitors, a total of 787 units were subjected to special screening. Of that number, 100 failed to meet the post test requirements. In view of the fact that the capacitors were not screened prior to the start of the test, this performance is considered above average.

SCREENING VERIFICATION TESTS

Following the special screening tests, three units from each of the 12 test groups were tested to determine the effect, if any, of the special screening on selected electrical characteristics of the test capacitor. Three characteristics were to be evaluated.

- capacitance vs. temperature and frequency
- dielectric absorption
- thermally stimulated discharge

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A summary of the capacitance change with frequency at various temperatures is shown in Table IV. Test frequencies were 120, 1K, 10 K and 100 KHz; temperatures were 25°C, -55°C and +100°C. A review of the data indicates that, except at 100 KHz, there is little or no difference in the frequency characteristics between the two screening methods. The polysulfone lots were expected to be more stable, because of their inherent characteristics. At 100 KHz, the special screened lots are more stable; this is believed due to the stabilizing effect of the 50 temperature cycles and the 168 hours of exposure to 100°C during the screening test.

The capacitance change with temperature was not strongly affected by the screening test. The change increased with increasing frequency but was not substantially different between special screening and standard screening. The graphs of Figure 10 show the capacitance change with temperature at the various frequencies.

The dielectric absorption of the test samples was nearly identical for all groups. The polysulfone film units were slightly lower in value; however, this was anticipated because of the characteristics of the material. A typical response curve is shown in Figure 11. The test method used was that described in MIL-C-83421.

Thermally stimulated discharge testing was performed on the three screening verification samples. The test procedure was as follows:

- Place test capacitor in an oven at 125°C.
- Apply 30 VDC for 1 hour.
- Cool to room temperature with voltage applied.
- Discharge capacitor through 1000Ω resistor for 30 seconds.
- Connect electrometer to capacitor terminals to measure current in nano-amperes.

TABLE IV

CAPACITANCE CHANGE WITH FREQUENCY AT INDICATED TEMPERATURES

TEST GROUP	CAPACITANCE CHANGE IN PERCENT								
	120 HZ TO 1 KHZ			10 KHZ TO 1 KHZ			100 KHZ TO 1 KHZ		
	25°C	-55°C	+100°C	25°C	+55°C	+100°C	25°C	-55°C	+100°C
SPCAX	+0.03	+0.44	+0.13	+0.09	-0.42	+0.18	+11.8	+ 9.7	+12.2
SPCAY	+0.03	+0.43	+0.12	+0.05	-0.44	+0.16	+ 8.8	+ 6.7	+ 9.5
SPCBX	+0.09	+0.44	+0.10	+0.07	-0.42	+0.19	+10.7	+ 8.7	+11.3
SPCBY	+0.09	+0.43	+0.09	+0.01	-0.45	+0.12	+ 8.0	+ 6.4	+ 8.7
DPCAX	+0.05	+0.42	+0.13	+0.09	-0.44	+0.21	+17.9	+15.2	+18.5
DPCAY	+0.11	+0.42	+0.02	0	-0.47	+0.12	+ 6.8	+ 6.1	+ 7.2
SPCCX	+0.09	+0.40	+0.10	+0.09	-0.40	+0.20	+12.8	+11.0	+13.7
SPCCY	+0.08	+0.47	+0.05	+0.03	-0.50	+0.15	+ 7.4	+ 5.5	+ 8.3
DTPDX	+0.06	+0.42	+0.18	+0.05	+0.42	+0.18	+15.2	+12.8	+18.6
DTPDY	+0.02	+0.41	+0.10	+0.04	+0.44	+0.14	+ 8.1	+ 5.9	+ 7.4
SPSAX	+0.08	+0.16	+0.13	+0.05	-0.06	+0.11	+ 6.7	+ 5.8	+ 7.5
SPSAY	+0.06	+0.15	+0.14	+0.07	-0.04	+0.13	+ 6.0	+ 5.2	+ 6.6

NOTE: Values shown are the average for the three (3) units in the screening verification test sample.

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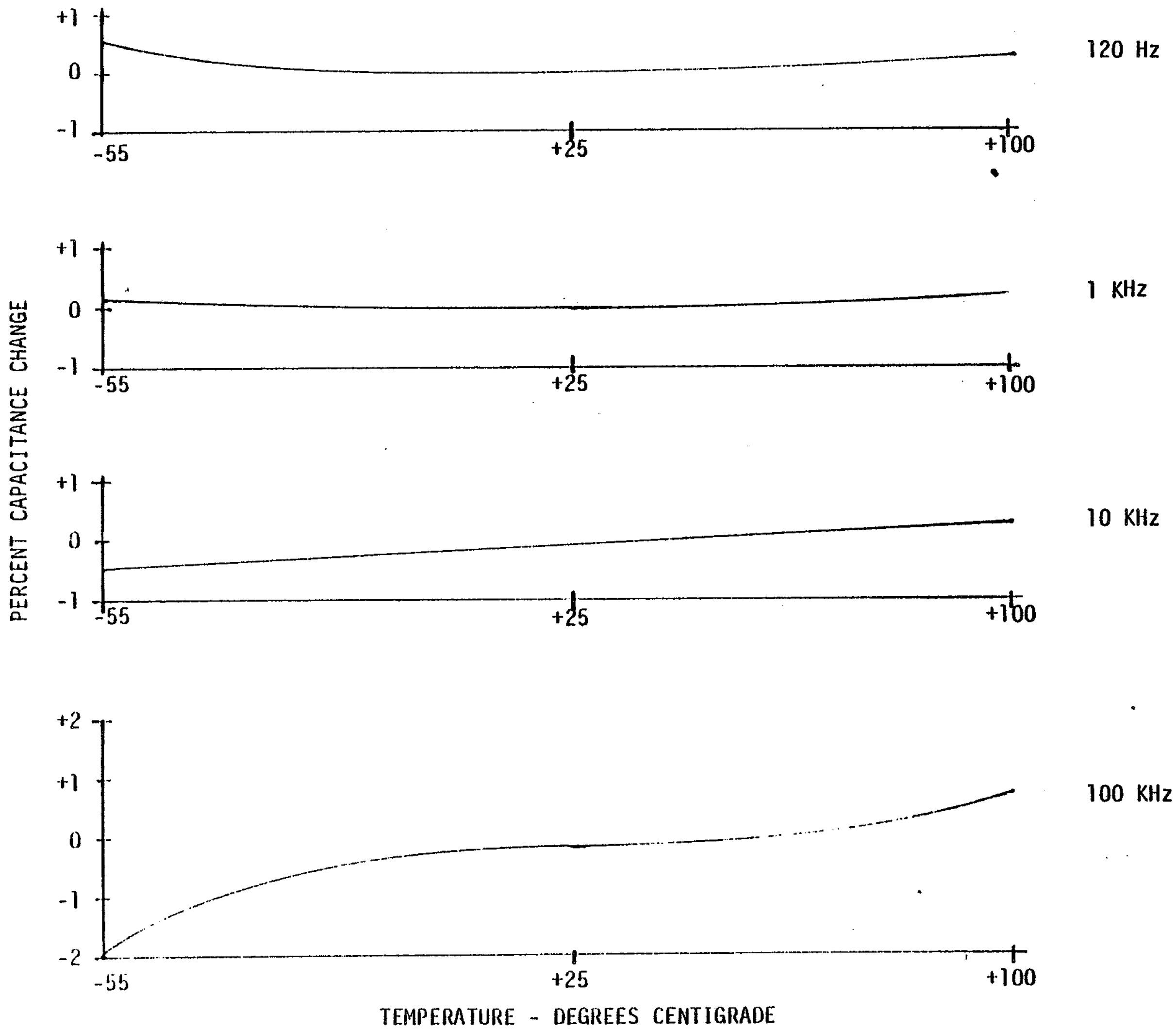
FIGURE 10

CAPACITANCE CHANGE WITH TEMPERATURE AT VARIOUS FREQUENCIES



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- Place capacitor in an oven and raise the temperature at $\sim$2°C/minute from 25°C to 125°C.
- Measure and record current at each interval

The test is reported[3/] to detect hidden charges in the dielectric and to show instabilities in the dielectric which may affect capacitor performance.

A typical TSD curve is shown in Figure 12. No significant difference was noted between the various types and groups with regard to this parameter.

It can generally be said that there were only minor differences in performance between special screened groups and MIL screened groups. Except for a slight improvement in capacitance stability for the special screened groups, the test units were very similar in performance characteristics.

ENVIRONMENTAL TEST PROGRAM

To evaluate the potential difference in the performance of capacitors screened by the proposed techniques, a series of environmental tests was suggested. The tests combined thermal, mechanical and electrical stress, under accelerated conditions, to which the capacitors would be subjected. The ramp test, with scan, was performed at selected readout intervals to monitor progress and failures. The environmental program consisted of the following:

Temperature Cycle

Method 107, MIL-STD-202

The following exceptions and conditions apply:

- Test Condition Letter - B
- Maximum Temperature - 100°C

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FIGURE 11

TYPICAL DIELECTRIC ABSORPTION CURVE

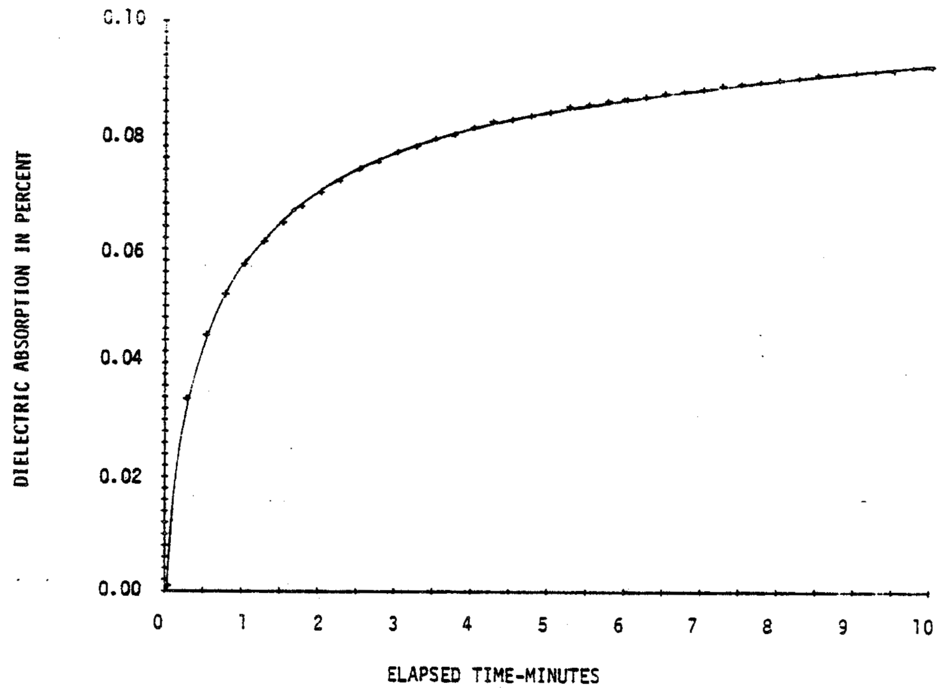
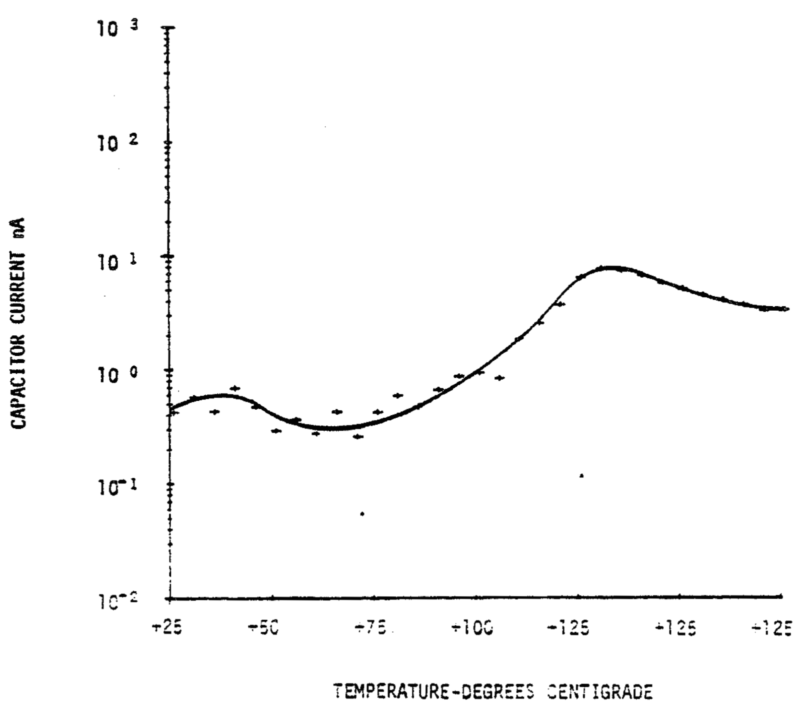


FIGURE 12

TYPICAL THERMALLY STIMULATED DISCHARGE RESPONSE CURVE



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- Number of Cycles - 300
- Ramp test with scan and 1 KHz and 10 KHz capacitance and dissipation factor at 10, 50, 100, 200 and 300 cycles

High Temperature Storage

- Test Temperature - 125°C
- Test Voltage - None
- Duration of Test - 2000 Hours
- Ramp test with scan and 1 KHz and 10 KHz capacitance and dissipation factor at 100, 500, 1000 and 2000 hours

Low Voltage Life Test

- Test Temperature - 25°C
- Test Voltage - 2.5 VDC
- Duration of Test - 2000 Hours
- Ramp test with scan and 1 KHz and 10 KHz capacitance and dissipation factor at 100, 500, 1000 and 2000 hours

Medium Voltage Life Test

- Test Temperature - 25°C
- Test Voltage - 5.7 VDC
- Duration of Test - 2000 Hours
- Ramp test with scan and 1 KHz and 10 KHz capacitance and dissipation factor at 100, 500, 1000 and 2000 hours

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High Voltage Life Test

- Test Temperature - 25°C
- Test Voltage - 30 VDC
- Duration of Test - 2000 Hours
- Ramp test with scan and 1 KHz and 10 KHz capacitance and dissipation factor at 100, 500, 1000 and 2000 hours

Each of the 5 test modules contained 240 capacitors, 20 from each test group. The groups were positioned in the ramp test chamber in different sequences to prevent chamber location from affecting capacitor performance. Figure 13 shows the oven locations for each test group and module.

A capacitor was classified as a failure if the post test electrical measurements failed to comply with the requirements specified in MIL-C-83421. Capacitors which faulted and cleared were classified as faults. Once a capacitor faulted, it remained classified as a fault unless it became a failure. Capacitors which faulted on repeat tests were only counted as one fault. Capacitors which faulted and cleared but later failed were classified as failures. Short circuit failures tend to appear, in the capacitance and D.F. data, to be very high in capacitance and, therefore, post test ΔC values for those units are artificial. These were not included in the calculations for average values of ΔC post test. Units having low insulation resistance (less than 10 MΩ) for periods of 30 seconds or greater were classified as short circuits by the ramp test. These could possibly clear during later stages of the testing and were recorded as faults.

In order to assess the effect of faulting and clearing on the performance of capacitors on the environmental test program, a number of units,

TEST GROUP IDENTIFICATION

GROUP CODE	GROUP IDENTIFICATION
A	SPCAX
B	SPCAY
C	SPCBX
D	SPCBY
E	SPCBX
F	SPCCY
G	DPCAX
H	DPCAY
I	DTPAX
J	DTPAY
K	SPSAX
L	SPSAY

TEST POSITION LOCATION

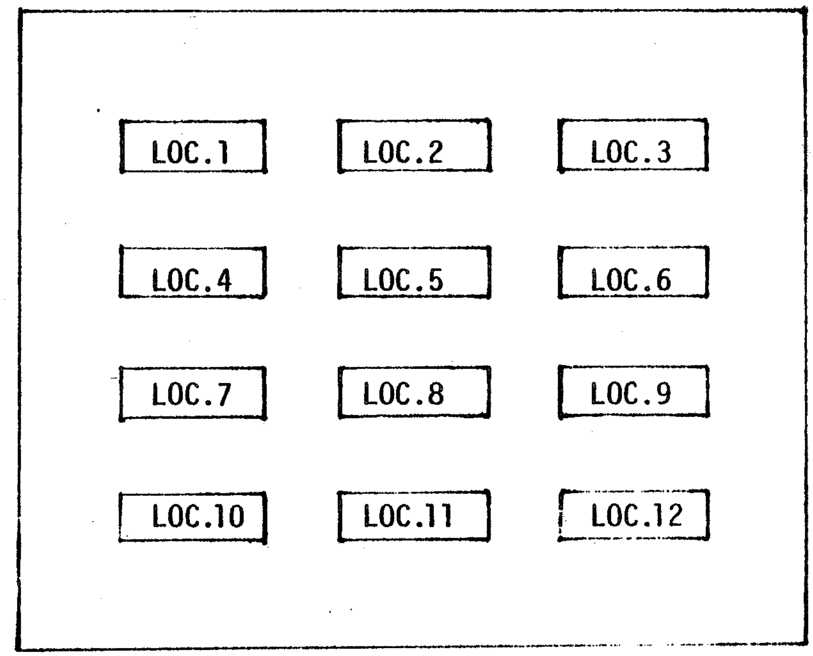
DOOR LOCATION	TEST POSITION
1	0-19
2	20-39
3	40-59
4	60-79
5	80-99
6	100-119
7	120-139
8	140-159
9	160-179
10	180-199
11	200-219
12	220-239

TEST GROUP LOCATION

DOOR LOCATION	T.C.	H.T.S.	LTL	LTM	LTH
1	A	J	B	C	L
2	B	G	I	F	K
3	C	K	H	B	J
4	D	L	C	A	I
5	E	H	L	E	H
6	F	D	K	L	G
7	G	I	D	K	F
8	H	E	F	D	E
9	I	A	G	I	D
10	J	F	A	H	C
11	K	B	E	J	B
12	L	C	J	G	A

NOTES: T.C. = TEMPERATURE CYCLE
H.T.S. = HIGH TEMPERATURE STORAGE
L.T.L. = LOW VOLTAGE LIFE
L.T.M. = MEDIUM VOLTAGE LIFE
L.T.N. = HIGH VOLTAGE LIFE

TEST DOOR LAYOUT



NOTE: DOOR LOCATIONS AS VIEWED FROM FRONT WITH DOOR MOUNTED TO CHAMBER.

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FIGURE 13

POSITIONING OF TEST GROUPS IN CHAMBER

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which had faulted during the screening test, were included in the various modules of the test matrix. These were dispersed throughout the matrix as shown in Table V.

TABLE V

DISTRIBUTION OF CAPACITORS WHICH FAULTED AND CLEARED DURING SPECIAL SCREENING TEST

TEST MODULE	NO. UNITS EXHIBITING FAULTING-BY TEST GROUP						
	SPCAY	SPCBY	SPCCY	DPCAY	DTPDY	SPSAY	TOTAL
TEMPERATURE CYCLE	0	1	0	1	4	8	14
HIGH TEMPERATURE STORAGE	2	1	4	2	4	5	18
LOW VOLTAGE LIFE (2.5V)	2	0	3	0	3	10	18
MEDIUM VOLTAGE LIFE (5.7V)	0	0	3	3	5	11	22
HIGH VOLTAGE LIFE (30V)	2	3	0	0	0	14	19
TOTALS	6	5	10	6	16	48	91

TEMPERATURE CYCLE TEST DATA

The data generated by the ramp testing during and after the temperature cycle testing are summarized in Table VI.

TABLE VI

SUMMARY OF TEMPERATURE CYCLE TEST DATA

TEST GROUP	SHORTS & IR FAILS	OPENS	FAULTS	POST TEST ΔC-%
SPCAX	1	3	3	+1.13
SPCAY	0	2	1	+1.02
SPCBX	0	1	2	+0.56
SPCBY	0	1	2	+0.32
SPCCX	0	1	2	+0.08
SPCCY	0	0	5	+0.22
DPCAX	7	1	1	+0.30
DPCAY	1	0	2	+0.13
DTPDX	8	1	0	+0.12
DTPDY	1	0	1	+0.12
SPSAX	0	0	1	+0.10
SPSAY	0	0	1	+0.10
TOTALS	18	10	21	
STANDARD SCREENED GROUPS	16	7	9	+0.38% (AVE.)
SPECIAL SCREENED GROUPS	2	3	12	+0.32% (AVE.)

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Of the 240 capacitors in the temperature cycle test module, 18 failed and an additional 21 faulted and cleared. Ten units were found to be open circuit when measured for capacitance. These are atypical failures and will be addressed in the section of this report entitled, "Analysis of Data and Failures".

The data show that the special screening test has been effective in reducing the number of failures (2 for special; 16 for standard screen). The correlation does not extend to units which faulted and cleared, as evidenced by the number of faulting units in each category (12 for special; 9 for standard screen). The following details were noted in the data for the 18 failures:

- 17 of the 18 failures "timed out" (insulation resistance <10MΩ for periods exceeding 30 seconds) during the ramp test at one or more of the readout intervals.
- 12 of 18 units exhibited faulting and clearing during the ramp test.
- 12 of 18 units faulted and cleared during more than one of the readout intervals, generally in 3 of the 5 intervals in the temperature cycle testing.

For units faulting and clearing, the data indicate that the energy used to clear a fault averages 31.5 μJ, with a minimum of 0.2 μJ and a maximum of 119 μJ. Of the 12 units which failed after faulting and clearing, the average energy used in clearing was 10.7 μJ, with a 0.3 μJ minimum and a 50.6 μJ maximum.

Post test capacitance change was well within specification limits as shown in Table VI. There appears to be no significant difference between the special and standard screened lots with regard to this parameter. The degradation of insulation resistance was well within acceptable limits, except for the failures previously noted. Post test values were approximately 70% of initial values.

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A number of capacitors which had faulted and cleared while on the special screening test were placed on the temperature cycle test to see whether capacitors which had faulted during special screening were more susceptible to failure than those not faulting. Table VII, below, lists those units and how they performed during the readout intervals and post test.

TABLE VII

PERFORMANCE OF UNITS FAULTING DURING SPECIAL SCREEN FOLLOWING TEMPERATURE CYCLE TESTING

TEST GROUP	UNITS FAULTING DURING SCREENING	FAULTING DURING RAMP TEST	POST TEST FAILURES
SPCAY	NONE	N/A	N/A
SPCBY	1	NONE	NONE
SPCCY	NONE	N/A	N/A
DPCAY	1	1	1
DTPDY	4	2	NONE
POLYCARBONATE GROUPS ONLY	6	3	1
PULYSULFONE GROUP ONLY	8	1	1
TOTALS FOR ALL GROUPS	14	4	2

These data show that there is not sufficient correlation between faulting during the special screening test and subsequent failure, as only 4 of 14 units repeated with only 2 failing. Considering only the polycarbonate units does not alter the trend; 3 of 6 repeated and only 1 of 6 subsequently failed.

HIGH TEMPERATURE STORAGE TEST DATA

The data generated by the ramp testing during and after the high temperature storage testing is summarized in Table VIII.

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TABLE VIII

SUMMARY OF HIGH TEMPERATURE STORAGE TEST DATA

TEST GROUP	SHORTS & IR FAILS	OPENS	FAULTS	POST TEST ΔC-%
SPCAX	18	0	1	+1.15
SPCAY	20	0	0	+1.29
SPCBX	2	0	3	+1.34
SPCBY	4	0	14	+1.35
SPCCX	3	0	5	+0.79
SPCCY	3	1	4	+1.4.
DPCAX	14	0	5	+0.68
DPCAY	11	0	8	+0.87
DTPDX	9	0	6	+0.25
DTPDY	10	0	7	+0.41
SPSAX	2	0	6	+0.22
SPSAY	3	0	4	+0.31
TOTALS	99	1	63	
STANDARD SCREENED GROUPS	48	0	26	+0.74%
CONTRACT SCREENED GROUPS	51	1	37	+0.94%

Of the 240 capacitors in the high temperature storage module, 99 failed and an additional 63 faulted and cleared. One capacitor failed open circuit and will be discussed in the section of this report entitled, "Analysis of Data and Failures".

The large number of failures generated during the high temperature storage test presented some difficulty in evaluating the performance of the capacitors on test. The special screening did not appear to improve reliability as it had in the temperature cycle testing groups reported earlier. This is believed due to the prolonged exposure at 125°C which apparently was too severe for the capacitors. No clear indications can be inferred from the data. The severity of the test is demonstrated by the large number of failures and faulting units (162 of 240).

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The following details were noted in the data for the failures:

- 57 of the 99 failures "timed out" (insulation resistance <10 MΩ for periods exceeding 30 seconds) during the ramp test at one or more of the readout intervals.

- 87 of the 99 failures experienced faulting and clearing during the ramp test at one or more of the readout intervals.

The average energy used to clear a fault in the 63 capacitors which faulted and cleared was 28.5 μJ, with a minimum of 0.9 μJ and a maximum of 139 μJ. For the units which failed after faulting and clearing, the average energy used in clearing was 12.6 μJ, with a minimum of 0.2 μJ and a maximum of 53.2 μJ.

The post test capacitance change was within specification limits of ±2%, and the post test insulation resistance was well within the limit specified in MIL-C-83421 for this parameter (33.3% of initial value). The values were approximately 60% of initial values.

The correlation between capacitors which faulted and cleared during special screening and subsequent performance on the high temperature storage test is presented in Table IX.

TABLE IX

PERFORMANCE OF UNITS FAULTING DURING SPECIAL SCREEN FOLLOWING HIGH TEMPERATURE STORAGE TESTING

TEST GROUP	UNITS FAULTING DURING SCREENING	FAULTING DURING RAMP TEST	POST TEST FAILURES
SPCAY	2	2	2
SPCBY	1	1	NONE
SPCCY	4	3	2
DPCAY	2	2	0
DTPDY	4	3	3
POLYCARBONATE GROUPS ONLY	13	11	7
POLYSULFONE GROUP ONLY	5	0	0
TOTALS FOR ALL GROUPS	18	11	7

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As in the temperature cycle test groups, the data do not support the correlation between faulting during special screening and failure. Only 7 of the 18 units included in the test module failed and, if only the polycarbonate units are considered, 7 of 13 failed.

LIFE TEST DATA

The data generated by the ramp test during and after the voltage life testing is presented in Table X. The table summarizes the data from each of three life test modules.

Of the 720 capacitors tested at the three life test conditions, only one failure was realized. Accordingly, no significance can be attached to the failure, although it did occur in one of the standard screened test groups. The following observations were made:

The number of units faulting and clearing varied directly with the applied voltage, i.e., 8 in the 2.5 volt groups, 11 in the 5.7 volt groups and 14 in the 30 volt groups.

Special screening appeared to reduce the number of capacitors faulting and clearing during the ramp test. This is evidenced by the lower number of faulting units in the special screened groups (13 vs. 20).

Low voltages did not adversely impact on the life test performance, or on the ability of the capacitors to clear.

The range of energy used to clear faults in each of the life test modules was as follows:

2.5 volt test -	23.6 μJ	average
	0.8 μJ	minimum
	69.6 μJ	maximum
5.7 volt test -	39.5 μJ	average
	7.2 μJ	minimum
	92.1 μJ	maximum
30 volt test -	33.6 μJ	average
	1.5 μJ	minimum
	117.0 μJ	maximum

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TABLE X

SUMMARY OF LIFE TEST DATA

SUMMARY OF 2.5 VOLT LIFE TEST DATA

TEST GROUP	SHORTS & IR FAILS	FAULTS
SPCAX	0	2
SPCAY	0	0
SPCBX	0	0
SPCBY	0	0
SPCCX	0	1
SPCCY	0	1
DPCAX	0	0
DPCAY	0	1
DTPDX	0	2
DTPDY	0	2
SPSAX	0	0
SPSAY	0	0
TOTALS	0	9
STANDARD SCREENED GROUPS	0	5
SPECIAL SCREENED GROUPS	0	4

SUMMARY OF 5.7 VOLT LIFE TEST DATA

TEST GROUP	SHORTS & IR FAILS	FAULTS
SPCAX	0	1
SPCAY	0	0
SPCBX	0	3
SPCBY	0	0
SPCCX	0	0
SPCCY	0	3
DPCAX	1	1
DPCAY	0	0
DTPDX	0	0
DTPDY	0	0
SPSAX	0	3
SPSAY	0	0
TOTALS	1	11
STANDARD SCREENED GROUPS	1	8
SPECIAL SCREENED GROUPS	0	3

SUMMARY OF 30 VOLT LIFE TEST DATA

TEST GROUP	SHORTS & IR FAILS	FAULTS
SPCAX	0	0
SPCAY	0	1
SPCBX	0	1
SPCBY	0	1
SPCCX	0	1
SPCCY	0	3
DPCAX	0	1
DPCAY	0	0
DTPDX	0	2
DTPDY	0	1
SPSAX	0	3
SPSAY	0	0
TOTALS	0	14
STANDARD SCREENED GROUPS	0	8
SPECIAL SCREENED GROUPS	0	6

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It should be noted that the faults were detected during ramp test, where the voltages applied to the capacitor range from 0 to 5 volts and 0 to 30 volts.

The data in Table X does not include capacitance change data, because, since the tests were run at room temperature, no significant change was observed. Also, the post test insulation resistance was well within specification limits at approximately 80% of initial values.

A summary of the data generated during ramp testing comparing performance by test module and screening type is presented in Table XI.

TABLE XI

SUMMARY OF TEST DATA BY MODULE AND SCREENING TEST TYPE

TEST MODULE	FAILURES AND FAULTING UNITS			
	SPECIAL SCREENING		STANDARD SCREENING	
	FAILS ONLY	COMBINED	FAILS ONLY	COMBINED
TEMPERATURE CYCLE	2	14	16	25
HIGH TEMPERATURE STORAGE	51	88	48	74
2.5 VOLT LIFE	0	4	0	5
5.7 VOLT LIFE	0	3	1	9
30 VOLT LIFE	0	6	0	8
TOTALS	53	115	65	121

These data indicate that the capacitors which were subjected to the special screening had less failures (45% vs. 55%) than the companion groups. The number of units faulting and clearing did not appear to be a function of the screening test. The effect of the high temperature storage test on the data is easily seen in the table. These represent 84% of the failures and 74% of all events (faults and fails).

An observation from the data indicated that capacitor reliability varied with raw material lots. A summary of the data by raw material lot and test module is presented in Table XII.

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TABLE XII

SUMMARY OF SHORT CIRCUIT FAILURES BY TEST AND MATERIAL LOT

RAW MATERIAL	TEMP. CYCLE	HI-TEMP. STORAGE	2.5 VOLT LIFE	5.7 VOLT LIFE	30 VOLT LIFE	TOTAL
A1	1	38	0	0	0	39
A2	8	25	0	1	0	34
B	0	6	0	0	0	6
C	0	6	0	0	0	6
D	9	19	0	0	0	28

NOTES: A1 = single layer lot A film
A2 = double layer lot A film
Only polycarbonate film units included in the summary.

These data appear to indicate that material lot is a variable in capacitor performance. Also, since lots A and B were from one manufacturer and lots C and D were supplied by another, the probability that lot-to-lot variability is a significant factor in device performance appears very likely. Attempts to identify the specific differences between the material lots will be detailed in the section of this report entitled, "Analysis of Data and Failures".

ANALYSIS OF DATA AND FAILURES

The fault and failure data generated during the ramp testing is recorded on tape cassettes. Each run, including the screening test runs, is stored on its own individual tape. Printouts of the data were analyzed to evaluate the performance of each group and to provide bases for conclusions.

During the screening tests, 201 capacitors generated 598 faults, an average of $\sim$3 faults per unit. The mean value energy pulse recorded was $\sim$17 μJ, with a minimum of 1.0 and a maximum of 230 μJ. During the intermediate and final ramp tests, 236 capacitors generated 5974 faults, an average of $\sim$25 faults per capacitor. The mean value energy pulse was 5 μJ, with a minimum of 0.2 and a maximum of 130 μJ. The following characteristics were noted regarding failures and/or faults:

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- 80% to 90% of all units faulting and clearing repeated on subsequent, or alternate, ramp tests.
- 50% of units faulting and clearing subsequently failed to meet post test requirements.
- 5% to 10% of units faulting and clearing did so only once and did not repeat or fail.
- Most faults occurred during the 0 to 5 VDC ramp and during the transition from low temperature to high temperature.

An anticipated benefit from the screening test was that capacitors which cleared during screening and possibly susceptible to early failure would be eliminated from the test population. As the data indicate, however, no specific correlation could be established between capacitors faulting and clearing during screening test and the performance of the units on subsequent testing. Tabulated below is the distribution of capacitors which faulted during screening in the various test modules and their performance on the ramp test at intervals and post test.

PERFORMANCE OF UNITS FAULTING DURING SCREENING

CATEGORY	TEMP. CYCLE	HI-TEMP. STORAGE	2.5 VOLT LIFE	5.7 VOLT LIFE	30 VOLT LIFE	TOTAL
FAULTED DURING SCREEN	14	18	18	22	19	91
REPEAT FAULTED DURING RAMP	4	11	1	1	0	17
FAILED CATASTROPHICALLY	1	7	0	0	0	8

These data clearly indicate that faulting and clearing, by itself, is not a precursor of capacitor failure. Accordingly, the anticipated benefit was not realized. The screening test has demonstrated that it improves reliability by reducing failures, as indicated by data summaries discussed earlier.

The temperature cycle testing generated the most fault events, a total of 2520, which were generated by 39 capacitors. This represents slightly over 64 faults per capacitor during the 5 interval ramp tests. 7.5% of the units tested failed to meet the post test requirements. As previously noted, most

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faults occurred during the change from -55°C to +100°C and, in fact, the test generated some open circuit failures which were not expected. Analysis of these failures revealed fractures between the sprayed end connection and the terminal wire. These caused intermittent contacts during the temperature excursions and generated a large number of very low energy (<1 μJ) fault pulses. The reason for the fractures in the terminal connection area is believed due to the extended cycling to 125°C performed on the units prior to screening test (50 cycles; -65°C to +125°C), which overstressed the connections. Subsequent testing (300 cycles; -65°C to +100°C) caused the weakened connection to fracture. These open circuit failures and the fault events they generated are not included in the data evaluations either as failures or as faulting units to avoid introducing additional variables into the data analysis.

There were 18 short circuit failures—2 in the special screened groups and 16 in the standard (MIL) screened groups. These were analyzed by unrolling the winding and measuring the resistance and finding the point where it increased abruptly. The winding and film were then examined to detect potentional defects. Generally, the short circuit was found within the last 5 or 10 turns on the outer surface of the winding with the exact cause not readily defined. Some windings had slight wrinkles in the center of the film width in the outer turn area. Other windings examined were found to contain minor processing defects which were likely responsible for the early short circuit failures.

The detrimental effect of the 125°C exposure on polycarbonate film groups was evident in the high temperature storage testing. After the 2000 hour exposure at 125°C, 41.3% of the units failed to meet post test requirements. A total of 1230 faults were generated by 162 capacitors, an average

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of 8 faults per capacitor, most of which shorted and, therefore, did not fault often. In fact, the effects of the high temperature exposure was strong enough to mask all other effects, except those related to film type and lot. Special screened groups had 51 failures vs. 48 for standard (MIL) screened groups.

A significant performance advantage was found in the polysulfone groups. In all tests combined, the polysulfone groups exhibited 2.5% failures (5 of 200), while the polycarbonate groups generated 11.3% failures (113 of 1000). All except one of the polycarbonate failures were generated during the temperature cycle and high temperature testing (18 during T.C, 94 during H.T.S.). The improved performance of polusulfone film capacitors is believed due to its higher temperature capability and oxidation resistance. An operating temperature of 125°C may be too severe for polycarbonate film, which has a glass transition temperature of $\sim$140°C, but not so for polysulfone film with a glass transition temperature of $\sim$180°C. It is conjectured that, at a 100°C maximum operating temperature, the polycarbonate units would have performed with better reliability because the rate of degradation would have been less severe.

Analysis of selected failures from the high temperature storage test groups confirmed the assumptions. The polycarbonate film had become discolored and exhibited poor tensile strength, particularly in the area of the outer turns. The film also crumbled readily when rubbed between the fingers. After unrolling the outer tenth or fourth of the winding turns, the film was found to be more normal, although still slightly weaker in tensile strength. Physical and chemical analysis of film, both as received and from tested capacitors, is being performed to quantify the differences. In addition,

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residual gas analyses are planned to determine if the gaseous species vary for capacitors which have failed as compared with those that have not failed.

The life test data were grouped together, since only 1 unit of the 720 tested at the three voltages failed to meet the post test requirement. Thirty-five (35) capacitors generated 2220 faults for an average of ~60 per capacitor. The largest number, 1420, were generated during the 30 volt life test; however, the only failure occurred in the medium voltage (5.7 VDC; 75 μJ) group. These results indicate that, at 25°C, voltage life is reliable even at low voltage and is relatively unaffected by external effects.

The distribution of failures and faulting units by test groups are shown in Figures 14, 15 and 16.

The distribution of failures was compared, also, on the basis of raw material lots. Capacitors made from lot A film, both single and double layer, exhibited more failures than lots B and C. A comparison of the failures by film lot is tabulated below for the test groups.

FAILURES BY FILM LOT AND TEST GROUP

FILM LOT	FAILURES BY TEST GROUP			
	TEMP. CYCLE	HI-TEMP. STORAGE	LIFE TESTS	TOTAL
LOT A	9	63	1	73
LOT B	0	6	0	6
LOT C	0	6	0	6
LOT D	9	19	0	28
POLYCARBONATE FILM TOTALS	18	94	1	113
POLYSULFONE FILM TOTALS	0	5	0	5
GRAND TOTALS	18	99	1	118

NOTES: Lot A contains single and double layer film.
Lots A and B are from the same manufacturer.
Lots C and D are from the same manufacturer.
Lot D uses 3.5 μm thick film.

FIGURE [illegible]

DISTRIBUTION OF FAILURES AND FAULTING UNITS DURING TEMPERATURE CYCLE TESTING

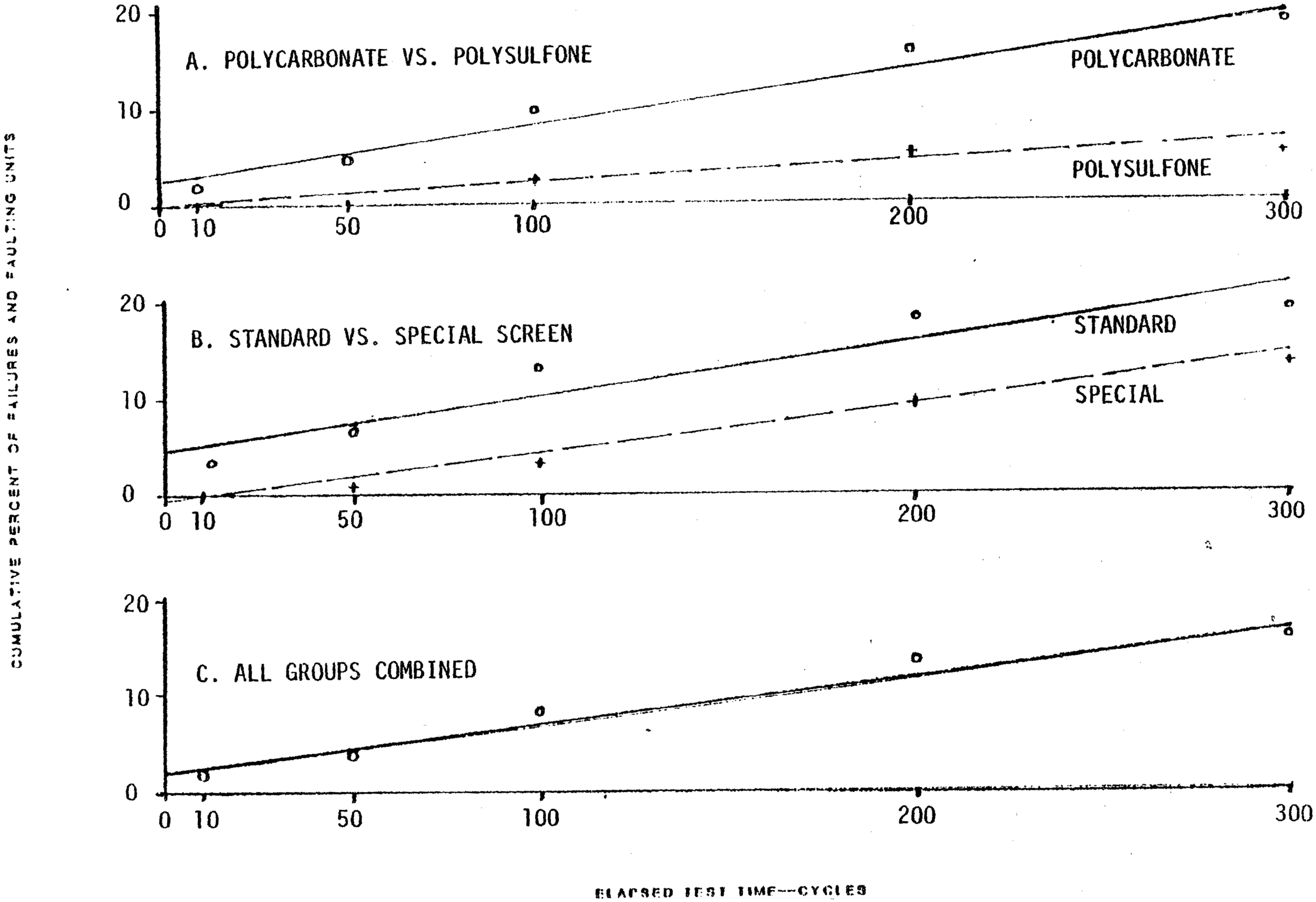

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FIGURE 15

DISTRIBUTION OF FAILURES AND FAULTING UNITS DURING HEAT SOAK TESTING

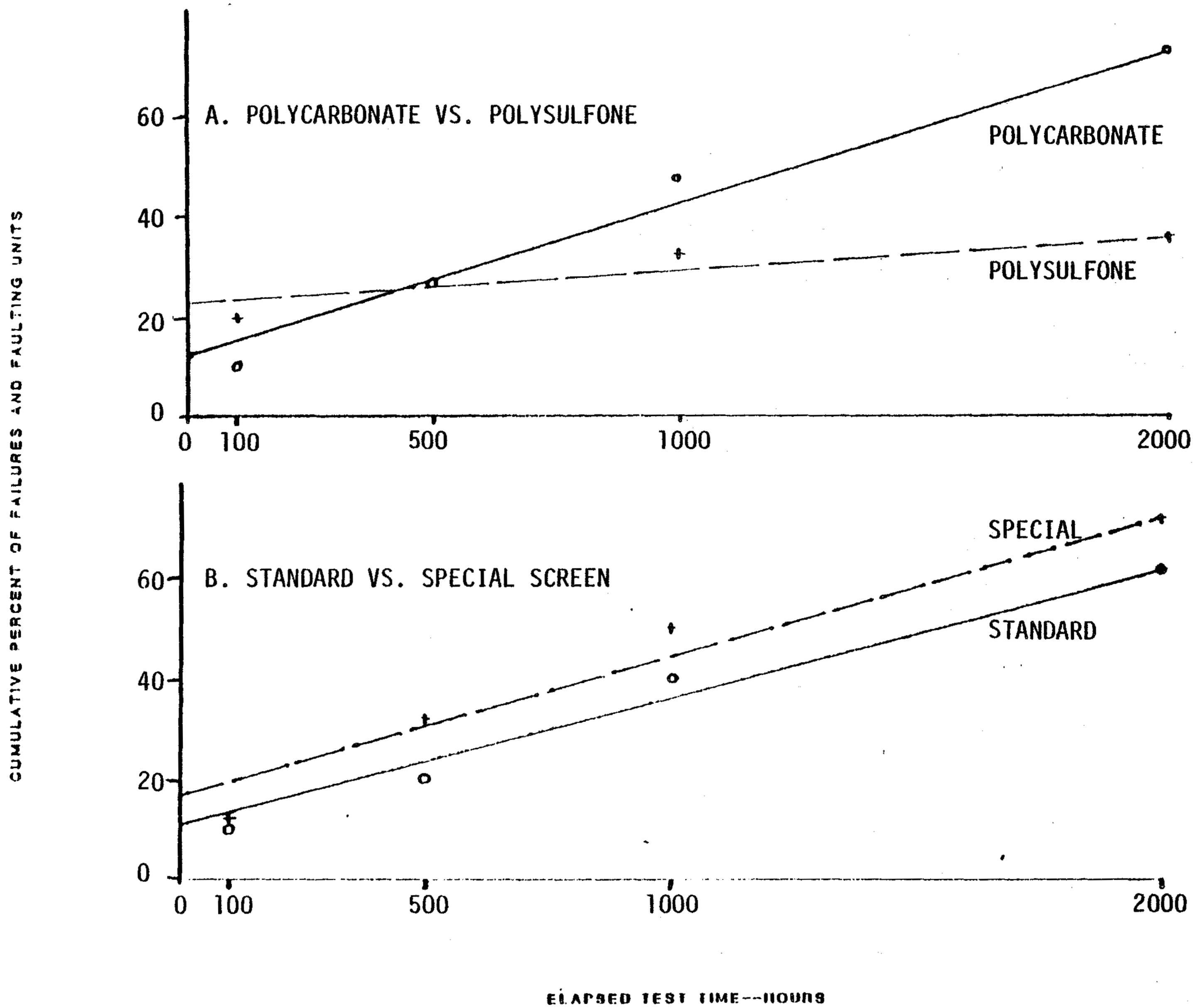

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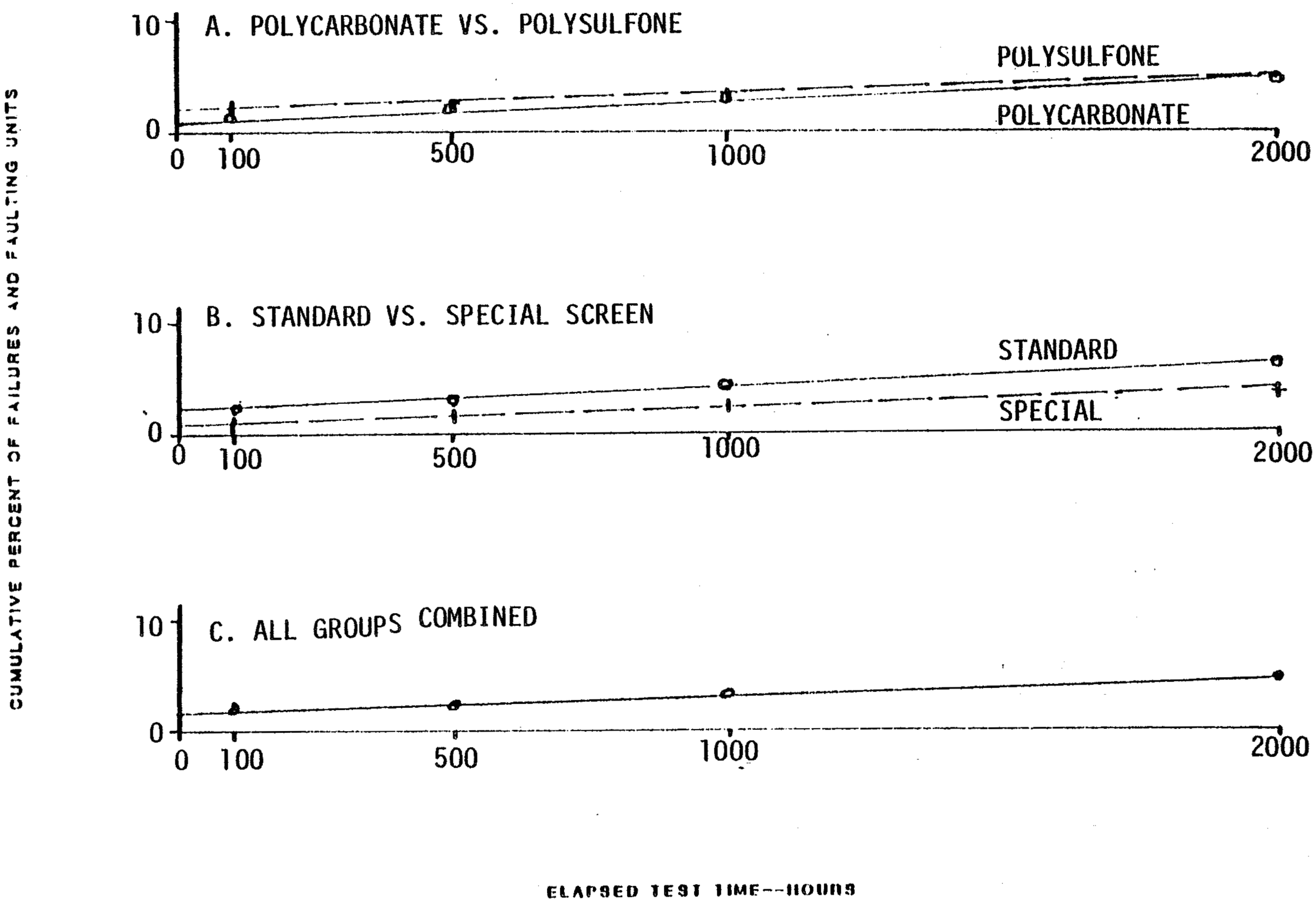
FIGURE 16

DISTRIBUTION OF FAILURES AND FAULTING UNITS DURING LIFE TESTING



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These data incidate that lots B and C performed significantly better than lots A or D and compared favorably with the polysulfone test groups. This was evidenced in both the severest environmental test groups and suggested very strongly that the starting raw material was a factor affecting device reliability.

Since raw material lot seemed a contributing factor, the determination of potential differences in the material was sought to provide criteria for material selection. Accordingly, samples from material lots A, B and C were subjected to the following tests:

- Thermogravimetric studies (TGA and DTA)
- Spectroscopic analyses (IR Spectra)
- Radiographic analysis (X-Ray Fluorescence)
- Analysis of solubles (Liquid Chromatography)

The thermogravimetric, spectroscopic and radiographic analyses failed to identify significant differences between the film lots. The analysis of solubles extracted in THF (tetra-hydro-furan) by liquid chromatography did reveal that the three lots tested (A, B and C) are different in chemical composition. Lot A has a significant volume of a low molecular weight species, whereas lots B and C have none, or only trace amounts of the same species. These samples are being concentrated and separated and will be analyzed by infra-red spectrophotometry to identify the specific chemical composition. If successful, this may yield a technique by which material can be selected, which has the best probability of producing capacitors which are highly reliable for these, as well as less severe applications.

Capacitors from the suspect film lot also were found to have more failures during the screening test. A summary, by film lot, is tabulated below.

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FILM LOT	FAILURES DURING SCREENING TEST
A1	25
A2	3
B	22
C	20
D	27

NOTES: A1 = single layer, Lot A film
A2 = double layer, Lot A film

Although these data do not provide as clear a difference in performance as does the environmental testing, the trend is discernible.

Lot D film performance is between the best and the worst of the other lots; however, it behaved very similarly to lot A, as shown by the summary of failures for the two lots, as tabulated below.

COMPARISON OF PERFORMANCE-LOT A VS. LOT D

FILM LOT	FAILURE BY TEST AND SCREEN TYPE					
	TEMPERATURE CYCLE		HI-TEMPERATURE STORAGE		LIFE TESTS	
	SPECIAL	STANDARD	SPECIAL	STANDARD	SPECIAL	STANDARD
A1	0	1	20	18	0	0
A2	1	7	14	11	0	1
D	1	8	10	9	0	0

Samples from film lot D were not available in as received condition, so were not included in the chemical analyses.

The testing to identify the chemical differences between film producing "good" and "bad" capacitors, as well as analyses of the gaseous species in tested and untested units, is in progress. These data will be incorporated into an addendum to this report.

Table XIII summarizes all the failures generated during environmental testing into the various categories — by screening technique, by dielectric material, by film lot and by a combination of film lot and screening technique.

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TABLE XIII

SUMMARY OF ALL FAILURES BY CATEGORY

CATEGORY	PERCENT FAILURES	FAILURES/STARTS
COMBINED	9.8	118/1200
MIL SCREENED	11.0	65/600
SPECIAL SCREENED	8.8	53/600
POLYCARBONATE	11.3	113/1000
POLYSULFONE	2.5	5/200
LOT A	18.3	73/400
LOT B	3.0	6/200
LOT C	3.0	6/200
3.5 μm FILM	14.0	28/200
LOT A (MIL)	20.5	41/200
LOT A (SPECIAL)	16.0	32/200
LOT B (MIL)	2.0	2/100
LOT B (SPECIAL)	4.0	4/100
LOT C (MIL)	3.0	3/100
LOT C (SPECIAL)	3.0	3/100
3.5 μm (MIL)	17.0	17/100
3.5 μm (SPECIAL)	11.0	11/100

By examining the table, the effect of each variable on capacitor performance can be estimated.

CONCLUSIONS

I. Screening Technique

The special screening technique was shown to be effective in enhancing device reliability. This was demonstrated by the smaller number of catastrophic failures in the special screened test groups. The number of failures for all test modules combined is summarized in the table below.

TEST MODULE	CATASTROPHIC FAILURES	
	SPECIAL SCREEN	MIL SCREEN
TEMPERATURE CYCLE	2	16
HIGH TEMPERATURE STORAGE	51	48
2.5 VOLT LIFE TEST	0	0
5.7 VOLT LIFE TEST	0	1
30 VOLT LIFE TEST	0	0
TOTALS	53	65

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Units which faulted and cleared were seemingly not affected by screening technique. Data show that special screened groups had 62 units faulting, while the MIL screened group had 56 units in the same category. The combined total of catastrophic failures plus faults also shows the special screening to be slightly more reliable with 115 units, as compared with 121 for the MIL screened groups.

Capacitors which faulted and cleared during the special screening test did not necessarily fault again, or fail catstrophically. It was hoped that this correlation could be established; however, since only 8 of 91 in this category ultimately failed, no correlation can be inferred.

The special screening test results generally correlated with the reliability of the test groups, i.e., those groups with more failures during screening test were also those with the greater number of failures during the environmental testing. The type of screening had only a minimal effect on the electrical characteristics of the capacitor tested. There is a slight improvement in the capacitance stability of the specially screened devices; however, this is believed due to the extended time on burn-in and its stabilizing effect on the winding.

II. Environmental Testing

Prolonged exposure at 125°C significantly affects the reliability of polycarbonate film capacitors and, to a much lesser degree, of polysulfone capacitors. The data show that greater than 80% of the total number of catastrophic failures recorded occurred in the polycarbonate test groups in the high temperature storage module. All five of the polysulfone test group failures were also recorded in this module. A comparison of the distribution of failures with and without the high temperature storage data is shown below.

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TEST MODULE	CATASTROPHIC FAILURES			
	ALL MODULES		LESS H.T.S. MODULE	
	SPECIAL SCREEN	MIL SCREEN	SPECIAL SCREEN	MIL SCREEN
TEMPERATURE CYCLE	2	16	2	16
Hi-TEMP. STORAGE	51	48	-	-
2.5 VOLT LIFE	0	0	0	0
5.7 VOLT LIFE	0	1	0	1
30 VOLT LIFE	0	0	0	0
TOTALS	53	65	2	17

The summary shows that 85% of all catastrophic failures occurred during the 125°C storage test. These data also show the significant improvement in the reliability of the special screened capacitors, which exhibit 2 failures, over the MIL screened groups, which had 17, if the high temperature storage data are not considered.

For the polysulfone film capacitors, all 5 of the failures were recorded in the high temperature storage test module, but there was no significant difference in the reliability of the capacitors based on screening technique.

The reliability of the test capacitors varied with raw material lot. One lot in particular, film lot A, yielded devices with lower reliability than the other material lots. The reliability, based on materials lot, is tabulated below.

FAILURE BY TEST MODULE

FILM LOT FILM LOT	TEMP. CYCLE	HI-TEMP STORAGE	LIFE TESTS	TOTALS
A SINGLE	1	38	0	39
A DOUBLE	8	25	1	34
B	0	6	0	6
C	0	6	0	6
3.5 μm	9	19	0	19

The data show that capacitors using film from lot A are much less reliable than those using lot B or C film. Material for the double layer windings was from the same resin lot as the film for the single layer windings and reinforces the poorer reliability of capacitors from lot A.

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Comparison by film lot and screening technique revealed that special screening, particularly if 125°C storage data are excluded, yields more reliable devices.

FAILURES BY TEST MODULE

	TEMP. CYCLE TYPE SCREEN		HI-TEMP. STORAGE TYPE SCREEN		LIFE TESTS TYPE SCREEN		TOTALS TYPE SCREEN	
FILM LOT	STD.	SPEC.	STD.	SPEC.	STD.	SPEC.	STD.	SPEC.
A SINGLE	1	0	18	20	0	0	19	20
A DOUBLE	7	1	15	11	1	0	23	12
B	0	0	2	4	0	0	2	4
C	0	0	3	3	0	0	3	3
3.5 μm	8	1	9	10	0	0	17	11

If high temperature storage data are deleted, the totals are as follows:

	TEMP. CYCLE TYPE SCREEN		LIFE TESTS TYPE SCREEN		TOTALS TYPE SCREEN	
FILM LOT	STD.	SPEC.	STD.	SPEC.	STD.	SPEC.
A SINGLE	1	0	0	0	1	0
A DOUBLE	7	1	1	0	7	1
B	0	0	0	0	0	0
C	0	0	0	0	0	0
3.5 μm	8	1	0	0	8	1

These data indicate that the special screening test may have improved the reliability of capacitors from film lot A, since MIL screened groups exhibit 8 failures and special screened lots only 1.

The improved reliability of polysulfone film capacitors compared to polycarbonate film units has been demonstrated by the data. Except for life tests, where only 1 failure was recorded, the polysulfone units had fewer failures than the polycarbonate capacitors. Five of the 200 polysulfone units tested failed (2.5%), while 113 of the 1000 polycarbonate capacitors failed (11.3%). In the high temperature storage test, the ratio of failures was 12.5% for polysulfone (5 of 40) and 47% for the polycarbonate (94 of 200). During the 25°C life tests, however, there was no significant difference in the reliability of capacitors using either film. This suggests that, if polycarbonate film

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is used at a lower temperature, possibly 65°C, or 85°C, the reliability will be improved significantly and may parallel that shown by the polysulfone film units at 125°C.

Two sheet insulating systems offer reliability advantages over single sheet systems. It is theorized that the multiple sheet system, because of its interleaved layer of clear (not metallized) film, is not as susceptible to faulting, because the additional insulation can stand off the applied voltage. The screening test data support this conclusion. Of all polycarbonate film capacitors using 2 μm film, and comparing single and double layer systems, the failures generated during the screening test were 50 of 393 (12.7%) for the single layer units and 3 of 120 (2.5%) for the double layer units. Once the capacitors were placed on environmental test, the improvement was not as clear. In the special screened groups, the advantage of the double layer construction was maintained; in the standard screened group, it was not as clear. These data are tabulated below for easy reference.

	NUMBER OF CATASTROPHIC FAILURES			
	STANDARD SCREEN		SPECIAL SCREEN	
TEST MODULE	SINGLE	DOUBLE	SINGLE	DOUBLE
TEMPERATURE CYCLE	1	7	0	1
HIGH TEMPERATURE STORAGE	23	15	27	11
2.5 VOLT LIFE	0	0	0	0
5.7 VOLT LIFE	0	1	0	0
30 VOLT LIFE	0	0	0	0
TOTALS	24	23	27	12

The data show the double sheet system to be more reliable than the single sheet system and that special screening significantly affected the result.

Of the units failing to meet the post test electrical requirements, the vast majority (∿95%) were shorted or failed to meet insulation resistance

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limits. The few open circuit failures encountered were due to the deleterious effect of the 125°C exposure on the capacitors.

The level of energy required to clear faults in metallized film capacitors is lower than anticipated. Clearing energy is defined as the amount of energy, in microjoules, that is used to effect fault clearing and represents the change in the energy stored in the capacitor as a result of the clearing. These clearing events routinely used less than 5 μJ and, often less than 1 μJ.

The amount of stored energy in the capacitor varied from 0.03 μJ to 2,250 μJ, but, for 70% of the ramp test time, did not exceed 62.5 μJ. The majority ($\sim$75%) of faults were recorded at voltages between 2 VDC and 5 VDC. These voltage levels represent 10 μJ and 62.5 μJ, respectively, and indicate clearing will occur with relatively low levels of energy stored in the capacitor. The estimated average is 20 μJ.

Fault clearing does not preclude or indicate failure. This is verified by the inclusion of capacitors which cleared during screening test and were subjected to environmental testing. A summary showing this relationship has been detailed elsewhere in this report but is tabulated below for easy reference.

	NUMBER OF UNITS PER TEST MODULE					
	TEMP.	HI-TEMP.	LIFE TESTS			
CATEGORY	CYCLE	STORAGE	2.5V	5.7V	30V	TOTALS
CLEARED DURING SCREEN	14	18	18	22	19	91
RECLEARED DURING RAMP	4	11	2	1	0	18
FAILED CATASTROPHICALLY	1	7	0	0	0	8

The data show that only 9% of the units which faulted during screening failed and 20% repeat cleared. If the 125°C storage test data are omitted, only 1.5% of subject units failed and 9.5% repeat cleared.

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The relationship between clearing energy used during screening test and catastrophic failure was also evaluated by comparing the clearing energy used by both capacitors which faulted and cleared only and those that failed.

CATEGORY	CLEARING ENERGY AVERAGE	MINIMUM	MAXIMUM
FAULTED AND CLEARED	35.8 μJ	9.0 μJ	109.0 μJ
CATASTROPHIC FAILURES	36.2 μJ	14.4 μJ	116.0 μJ

For all capacitors tested, Figure 17 compares the clearing energy used by both failures and faults. The data shows little difference in the clearing energy level between the two categories. Failures generated less clearing events than faults because, as shorts, they do not generate fault pulses. Accordingly, faults appear to have a slightly higher mean energy value. Based on these data, it is concluded that clearing energy is not a significant factor in predicting ultimate device failure.

All test groups demonstrated acceptable reliability data on life test, regardless of energy content in the capacitor. Only one unit, in the 5.7 volt test group (stored energy ~75 μJ), failed to meet post test requirements. No failures were recorded in either the 2.5 volt (~15 μJ) or the 30 volt (~2250 μJ) test groups. Of the 720 capacitors tested on all three life tests, only 34 units faulted and cleared during the intermediate and final ramp tests.

Raw material lots exhibit differences which may be related to capacitor reliability. The reliability of units from the various material lots has been documented elsewhere in this report. Physical and chemical analyses are in progress to characterize and identify these differences. Testing to date has identified that raw material from lot A has a slightly different composition than lots B and C and that it contains a significantly higher

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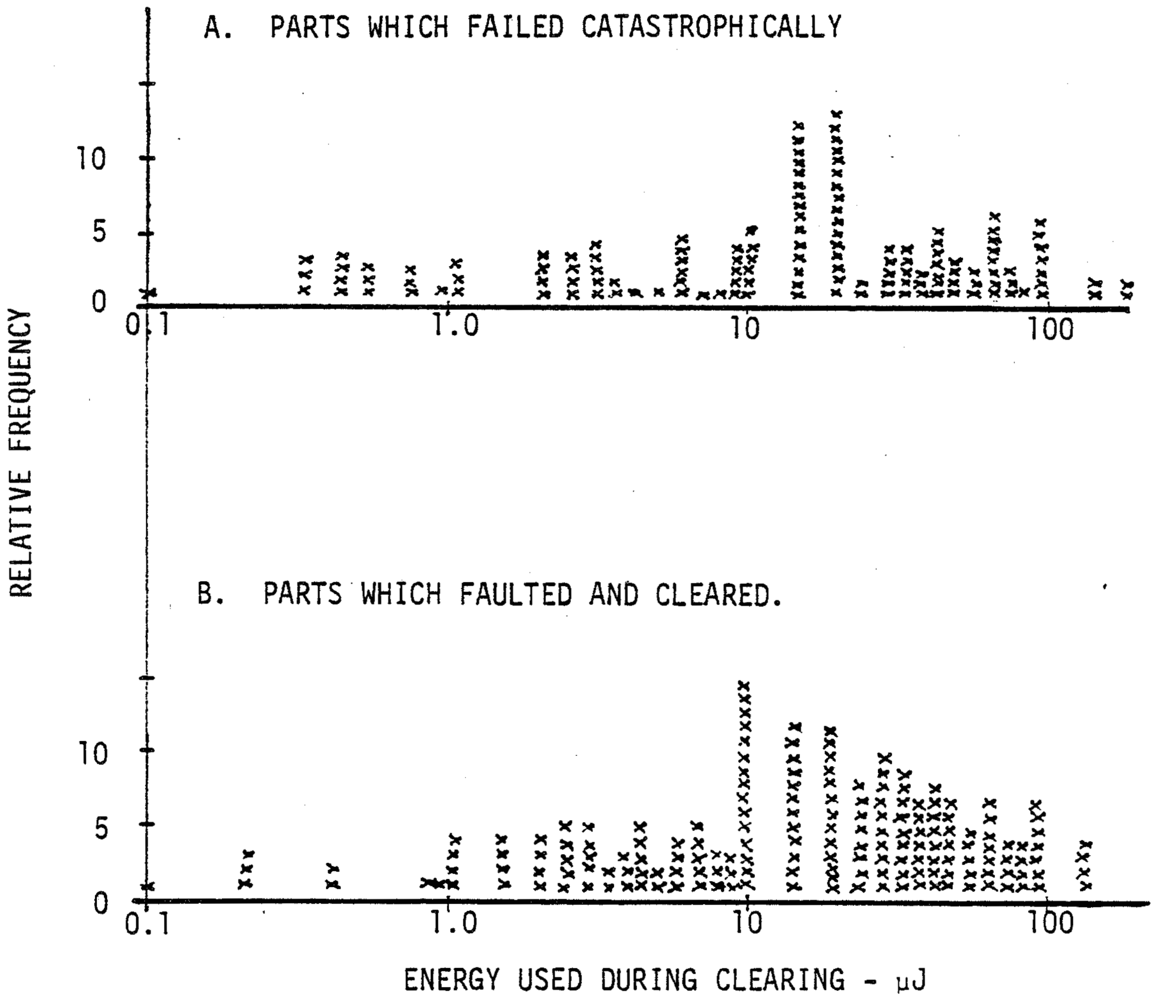


NOTE: CLEARING ENERGIES <1 μJ ARE LIKELY DUE TO SYSTEM NOISE AND SHOULD NOT BE CONSIDERED.

FIGURE 17

DISTRIBUTION OF CLEARING ENERGIES FOR FAILURES AND FAULTING UNITS

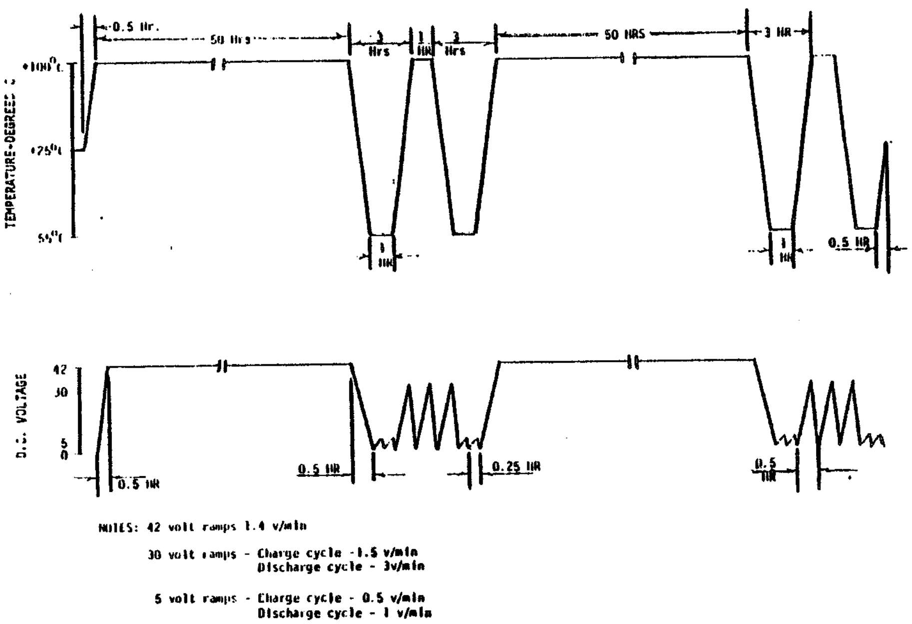
higher percentage of a low molecular weight compound. This compound will be identified and its potential effect on device reliability assessed. In addition, residual gas analyses are planned on tested and untested units from each material lot to attempt to identify causative factors or raw material differences. Results of these evaluations will be included in an addendum to this report.

RECOMMENDATIONS

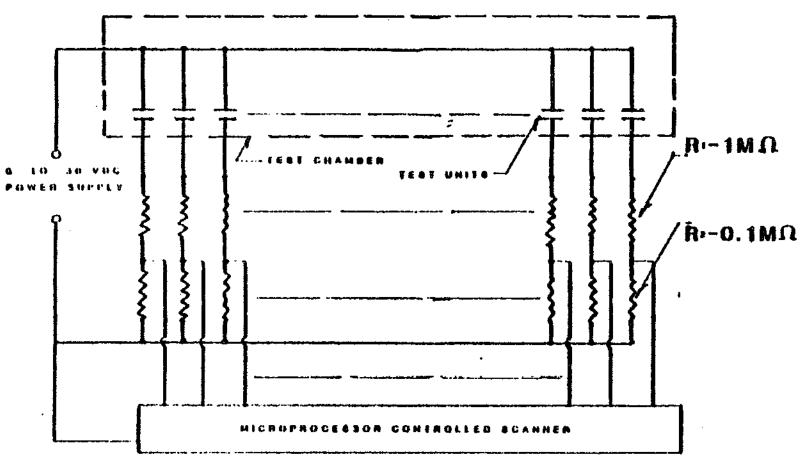
Based on the results of this study, six recommendations are offered.

1. Metallized film capacitors should be subjected to a screening technique to improve reliability. The following sequence of operations represents the recommended screen technique:
   - A. Temperature cycle; 50 cycles: -55°C to +100°C
   - B. Seal test - fine and gross leak
   - C. Capacitance and D.F. at 1 KHz, or applicable frequency, at 25°C
   - D. Test using the procedure outlined in Figure A
   - E. Measure insulation resistance at 30 VDC at 25°C and 100°C
   - F. Measure capacitance and DF at 1 KHz at 25°C (or at applicable frequency)
   - G. Seal test - fine and gross leak

2. The maximum use temperature for metallized polycarbonate capacitors should not exceed 100°C to improve reliability. For maximum reliability and stability of electrical characteristics, it is recommended that the upper temperature limit be restricted to +65°C. This value is comfortably below the first order transition temperature of polycarbonate film, which is $\sim$80°C.



TEMPERATURE AND VOLTAGE PROFILES



CAPACITOR TEST CIRCUIT

RECOMMENDED TEST PROCEDURE

1. Start at 25°C and 0 VDC.
2. Raise temperature to 100°C (0.5 hour).
3. Ramp voltage from 0 to 42 VDC at 1.4 V/min.
4. Hold at 42 VDC and 100°C for 50 hours.
5. Start temperature cycles shown and ramp voltage from 42 to 0 VDC at 1.4 V/min.
6. Perform sequence of 5 volt and 30 volt ramps during temperature cycling.
   - A. Temperature cycles to be 1 hour at each extreme and 1 hour for transition.
   - B. Voltage sequence is: 4 ramps 0-5-0 VDC, followed by
     6 ramps 0-30-0 VDC, followed by
     4 ramps 0-5-0 VDC, followed by
     ramp from 0 to 42 VDC at 1.4 V/min.
   - C. 5 volt ramps at 0.5 V/min. on charge cycle and 1 V/min. on discharge.
   - D. 30 volt ramps at 1.5 V/min. on charge cycles and 3 V/min on discharge.
7. Hold at 42 VDC and 100°C for 50 hours.
8. Repeat 6, 6A, 6B (except for 42 volt ramp), 6C and 6D.
9. Return chamber temperature to 25°C.
10. Measure insulation resistance at 25°C with 30 VDC applied.
11. Measure insulation resistance at 100°C with 30 VDC applied.
12. Measure capacitance and dissipation factor at desired frequency.

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FIGURE A

RECOMMENDED SCREENING TEST PROCEDURES, TEMPERATURE AND VOLTAGE PROFILES AND TEST CIRCUIT

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3. Where high temperature operation is essential, the use of polysulfone film dielectric is recommended. This study indicates that, at 125°C, capacitors using polysulfone film are significantly more reliable than those using polycarbonate film.

4. Raw material lots should be screened to identify film which may be unsatisfactory for use in capacitors for space applications. These findings should be provided to film manufacturers so that methods and techniques to control film quality may be instituted during the film manufacture. Specific recommendations regarding screening procedures will be included in an addendum to this report.

5. Metallized film capacitors are recommended for use in circuits and applications where occasional noise pulses do not adversely affect circuit behavior and characteristics. This study shows that, even in low voltage, high impedance circuits, metallized capacitors may fault and clear without failing catastrophically. Accordingly, if noise pulses or momentary changes in capacitor voltage and insulation resistance affect circuit performance, either circuit parameters should be adjusted to compensate for these pulses, or, metallized capacitors should not be used.

6. The minimum amount of stored energy in a capacitor which will permit clearing should exceed 100 uJ, but need not exceed 500 uJ. Data from this study has shown that clearing will occur routinely with 65 uJ stored in the capacitor and has been recorded with as little as 15 uJ stored energy. It is believed that, for the ratings studied, the recommended levels are adequate. Users should be aware that, on rare

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occasions, metallized capacitors may resist clearing, regardless of the energy stored in the capacitor. It is believed that such devices would be removed from the population during the proposed screening test.

FUTURE WORK

The present study has provided answers to the questions regarding screening tests, energy levels for fault clearing, material lot variability and device reliability. Some questions were raised during this work.

1. The reliability of polycarbonate film capacitors at temperatures 100°C and below should be ascertained. Tests at 65°C, 85°C and 100°C should be performed to provide these data.

2. Further work to clearly identify film properties and their impact on capacitor reliability should be performed. This may provide information to classify film lots to produce capacitors with optimized performance and reliability.

3. The performance of other films, such as polyester or polypropylene, should be considered. The present study shows polysulfone film to be highly reliable. Other films may perform satisfactorily.

4. An evaluation of other capacitance values should be considered. The present study tested capacitors with an average value of 5 uF; smaller and larger values are routinely used in normal application. It is conjectured that capacitor performance may be related to its electrode area. Studies to evaluate the effect of special screening on this variable would provide reliability data beneficial to circuit designers and other users.

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